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THESIS

A COMPARATIVE ANALYSIS OF SHIP SELF AIR DEFENSE (SSAD) SYSTEMS USING A MODKIT SIMULATION

By

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March 1999

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Rapid changes and developments in defense technology have created a difficult analytical environment for decision authorities when selecting the best weapon system for their armed forces. Appropriate operations analysis techniques and tools can provide some insight needed for the selection process. The objective of this thesis is to identify and develop suitable Operations Research analytical techniques and tools to aid decision authorities in the Ship Self Air Defense (SSAD) system selection process. The thesis first develops a SSAD system simulation Model (SSAD-Sim) using discrete event simulation techniques and implements it in the Java programming language and Modkit. The simulation is then used to identify appropriate exploratory analysis capabilities including measures of effectiveness evaluation and parameter sensitivity analysis. Exploratory analysis techniques are used to evaluate two different SSAD systems and firing policies. Key parameters analyzed for sensitivity include numbers of trackers, SAM inventory levels and tracker slew delay. As a result of the success of the SSAD simulation, further component additions and modifications are recommended for further study and development.

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A COMPARATIVE ANALYSIS OF SHIP SELF AIR DEFENSE (SSAD) SYSTEMS USING A MODKIT SIMULATION

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ABSTRACT

Rapid changes and developments in defense technology have created a difficult analytical environment for decision authorities when selecting the best weapon system for their armed forces. Appropriate operations analysis techniques and tools can provide some insight needed for the selection process. The objective of this thesis is to identify and develop suitable Operations Research analytical techniques and tools to aid decision authorities in the Ship Self Air Defense (SSAD) system selection process. The thesis first develops a SSAD system simulation Model (SSAD-Sim) using discrete event simulation techniques and implements it in the Java programming language and Modkit. The simulation is then used to identify appropriate exploratory analysis capabilities including measures of effectiveness evaluation and parameter sensitivity analysis. Exploratory analysis techniques are used to evaluate two different SSAD systems and firing policies. Key parameters analyzed for sensitivity include numbers of trackers, Surface-to-Air Missile (SAM) inventory levels and tracker slew delay. As a result of the success of the SSAD simulation, further component additions and modifications are recommended for further study and development.

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LIST OF SYMBOLS, ACRONYMS AND ABBREVIATIONS

ASM	Anti-Ship Missile
IR	Infrared
LOS	Line Of Sight
MOE	Measure Of Effectiveness
NM	Nautical Mile
OOP	Object Oriented Programming
OR	Operations Research
P_d	Probability of detection
$P_{noleakers}$	Probability of no leakers
RF	Radio Frequency
SAM	Surface to Air Missile
SAM P_{kill}	Surface to Air Missile kill probability
S-L-S	Shoot-Look-Shoot
SSAD	Ship Self Air Defense
SSAD-Sim	Ship Self Air Defense Simulation
S-S-L	Shoot-Shoot-Look
t_{ka}	Kill assessment time
t_{SALVO}	Salvo delay time

EXECUTIVE SUMMARY

Rapid changes and developments in defense technology have created a difficult analytical environment for decision authorities when selecting the best weapon system for their armed forces. Appropriate operations analysis techniques and tools can provide some insight needed for the selection process. The objective of this thesis is to identify and develop suitable Operations Research analytical techniques and tools to aid decision authorities in the Ship Self Air Defense (SSAD) system selection process. The thesis first develops a SSAD system simulation Model (SSAD-Sim) using discrete event simulation techniques and implements it in the Java programming language and Modkit. The simulation is then used to identify appropriate exploratory analysis capabilities including measures of effectiveness evaluation and parameter sensitivity analysis.

In an illustrative quick turnaround exploratory analysis, using unclassified data, the SSAD-Sim was run over 25,000 times to provide insights into the effectiveness of two different SSAD systems using two different firing policies. In stressing the SSAD system, initial results indicated that with a load out of 20 Surface-to-Air Missiles (SAMs), a Shoot-Shoot-Look (S-S-L) firing policy was preferred to Shoot-Look-Shoot (S-L-S) firing policy over a broad range of parameter values. The constraint of only being able to simultaneously illuminate two threat Anti-Ship Missiles (ASMs), in stressing scenarios, dominates even very high SAM P_{kill} values. The SSAD-Sim modeled suggests that an active SSAD system with an aggressive S-S-L firing policy be considered for further implications and analyses.

I. INTRODUCTION

A. BACKGROUND

Rapid changes and developments in defense technology have created a difficult analytical environment for decision authorities when selecting the best weapon system for their armed forces. Should a newly acquired and installed system be ineffective in performance trials, changing it with a more effective one seems almost impossible, due to extremely high costs and complicated replacement procedures. Worst of all, if this ineffective performance is not identified until actual combat, significant harm and possible loss to the combatants could occur.

As a result, decision makers must be provided with the best information possible during the competitive weapon system selection process. To do this effectively, we need tools that are reusable, easily expendable and that can be developed quickly. These analytical tools will allow decision makers to keep up with today's rapidly changing ship self air defense weapon and sensor capabilities and evolving threat scenarios.

B. THESIS OBJECTIVE

The objective of this thesis is to develop a simulation that provides suitable Operations Research (OR) analytical techniques and tools to aid decision authorities in the Ship Self Air Defense (SSAD) system selection process. The simulation will then be used to identify appropriate exploratory analysis capabilities including Measure of Effectiveness (MOE) evaluation and parameter sensitivity analysis.

C. RESEARCH QUESTIONS

This thesis addresses the following research questions:

- Can a simulation tool be developed that provides credible information to decision makers in the SSAD system selection process?
- What are the appropriate SSAD simulation analysis techniques and tools for evaluation of competitive SSAD systems?
- Which simulation measures of evaluation are most applicable for SSAD system selection?

D. METHODOLOGY

This thesis first develops a SSAD system simulation Model (SSAD-Sim) using discrete event simulation techniques and implements it in the Java programming Language and Modkit. Modkit is a Java™ package recently developed by Maj. Arent Arntzen, Norwegian Air Force. Secondly, it utilizes the model and exploratory analysis techniques to study two different SSAD systems and firing policies. Exploratory analysis is the use of a series of computational experiments to explore the implications of varying assumptions and hypotheses. For combat simulations such as this, it generally requires a large number of runs. [Ref. 1: pp. 435]

E. SCOPE OF THESIS

This thesis will use the Turkish Navy's SSAD system selection problem as a specific example. Currently, the Turkish Navy has to decide on the best SSAD system for installation on their newly built frigates for the 21st century. So far, two candidate SSAD systems have been introduced by two competitive companies, the Raytheon Company from the U.S. and the ASTER Company from France. A general SSAD system model is developed to represent SSAD systems that meets the Turkish Navy's need.

To demonstrate this model's utility, this thesis focuses on the effects of different SSAD system missile performances and firing policies. Thus, in this thesis, different

SSAD systems will be created using the same sensor, but with different types of SSAD system missiles.

Additionally, for the sake of simplicity, some aspects of the SSAD System are omitted in the SSAD Simulation (SSAD-Sim). As a result, this thesis makes the following general assumptions:

- Environmental Conditions (Weather, sea state...etc.) are not treated explicitly.
- Operator errors, differences between operators, and human factor effects are not modeled.
- "Soft Kill" counter measure systems of the ship (decoys, chaff, and radar jamming devices) are ignored.
- Radar is the only modeled surveillance system.
- The threat is considered as incoming missiles. No aircraft are modeled as a threat.

This thesis makes additional detailed assumptions for each element of the SSAD system. These assumptions are explained in detail in Chapter III of this thesis.

Since the classification level of this thesis is unclassified, it will use unclassified data and tactics.

F. PRINCIPLE FINDINGS

By using modern simulation techniques we can build a flexible and powerful analysis tool that can assist decision makers in evaluating different SSAD systems and tactics. In an illustrative quick turnaround exploratory analysis, using unclassified data, the SSAD-Sim was run over 25,000 times to provide insights into the effectiveness of two different SSAD systems using two different firing policies. In stressing the SSAD system, initial results indicated that with a load out of 20 Surface-to-Air Missiles (SAMs), a Shoot-Shoot-Look (S-S-L) firing policy was preferred to Shoot-Look-Shoot (S-L-S) firing policy over a broad range of parameter values. Figure 1 shows significantly improved survivability across a range of SAM effectiveness (probability of kill [SAM P_{kill}]) with a S-S-L firing policy. In fact, a S-S-L firing policy, with a 0.6 SAM

P_{kill}, has about the same effectiveness, in terms of the probability of no leakers, as a 0.8 SAM P_{kill} with S-L-S firing policy. Other runs revealed that this relationship holds true as long as the load out of SAMs is greater than seven.

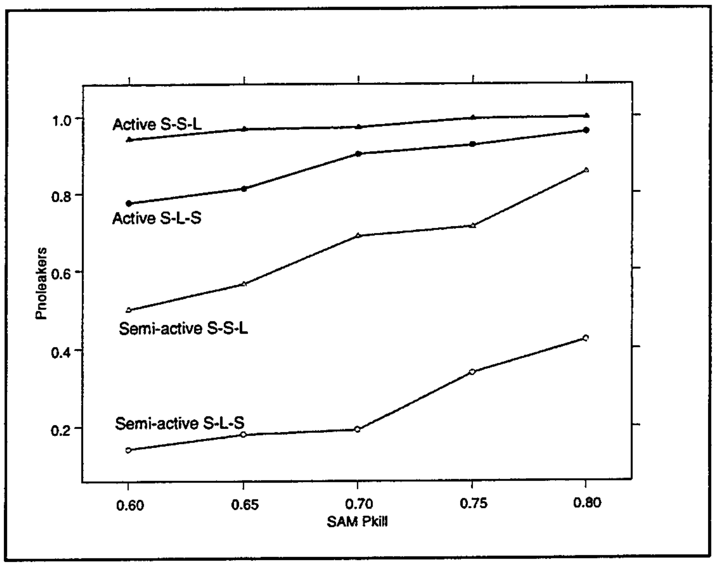


Figure 1. Probability of No Leakers versus SAM P_{kill} Values of the Active and the Semi-active SSAD Systems in a stressful scenario. (The ship, with a 20 SAMs load out, tries to defend itself against two approaching ASMs from the North and two approaching ASMs from the East with a six-second time interval between each other).

We also see in Figure 1 that, in this stressing case, an active SSAD system performs dramatically better than a semi-active one. In fact, an active system with a 0.6 SAM P_{kill}, using its best firing policy, is several times more survivable than a semi-active system with 0.8 SAM P_{kill}. This trend holds true even for unrealistically optimistic semi-active system performance (as quantified by tracker slew delays). The constraint of only being able to simultaneously illuminate two threat Anti-Ship Missiles (ASMs), in stressing scenarios, dominates even very high SAM P_{kill} values. The SSAD-Sim modeled suggests that an active SSAD system with an aggressive S-S-L firing policy be considered for further implications and analyses.

G. ORGANIZATION OF THESIS

This thesis is divided into six chapters.

Organization and general ideas for the following chapters are summarized as follows:

Chapter II- SSAD System Description. This chapter begins with the background information about Anti-Ship Missiles (ASMs), and then describes the SSAD system elements and the SSAD system process like that modeled and analyzed in this thesis.

Chapter III- SSAD-Simulation. This chapter first explains the programming tools, assumptions and components of SSAD-Sim. Second, it discusses the input and output values of SSAD-Sim. Finally, it creates two candidate SSAD systems in the database of SSAD-Sim.

Chapter IV- SSAD System Effectiveness Analysis. This chapter determines the related Measures of Effectiveness (MOEs) for SSAD systems, makes a comparative analysis, and determines the most effective SSAD system and firing policy.

Chapter V- Sensitivity Analysis Applications of SSAD-Sim. This chapter makes the sensitivity analyses of key parameters by using SSAD-Sim simulation results.

Chapter VI- Conclusions. This chapter reviews the results of the simulation. It then makes conclusions and necessary recommendations.

II. SHIP SELF AIR DEFENSE SYSTEM (SSAD) DESCRIPTION

This chapter describes the specific Ship Self Air Defense (SSAD) system which is modeled and analyzed in this thesis. To do this, this chapter uses the following order: first, background information about Anti-Ship Missiles (ASMs) (i.e., the threat) is explained. Second, the critical elements of the SSAD system are introduced. Third, the SSAD system process is described.

A. THE ANTI-SHIP MISSILE THREAT

In today's Naval Warfare, the attacker forces' main mission is to destroy or neutralize high valued sea forces. Compared with other anti-ship weapons, ASMs are considered the most effective and safe weapon system for the attacking forces.

Depending on the launching platforms, ASMs are divided into two types: air-launched ASMs and surface-launched ASMs. Air-launched ASMs are launched from attack aircraft or rotary wing aircraft (helicopters). Whereas, surface-launched ASMs are launched from land, boats, ships, or submarines. Most of ASMs have long enough ranges to be launched from over-the-horizon. In over-the-horizon launches, launch platforms gather the targeting data via radio frequency (RF) links from remote sensors. Aircraft sensor platforms and satellites are two primary sources of targeting data for ASMs. On the other hand, ships or land sites can also perform the targeting function. [Ref. 2: pp.7-18] Figure 2 illustrates various delivery and targeting methods for ASMs.

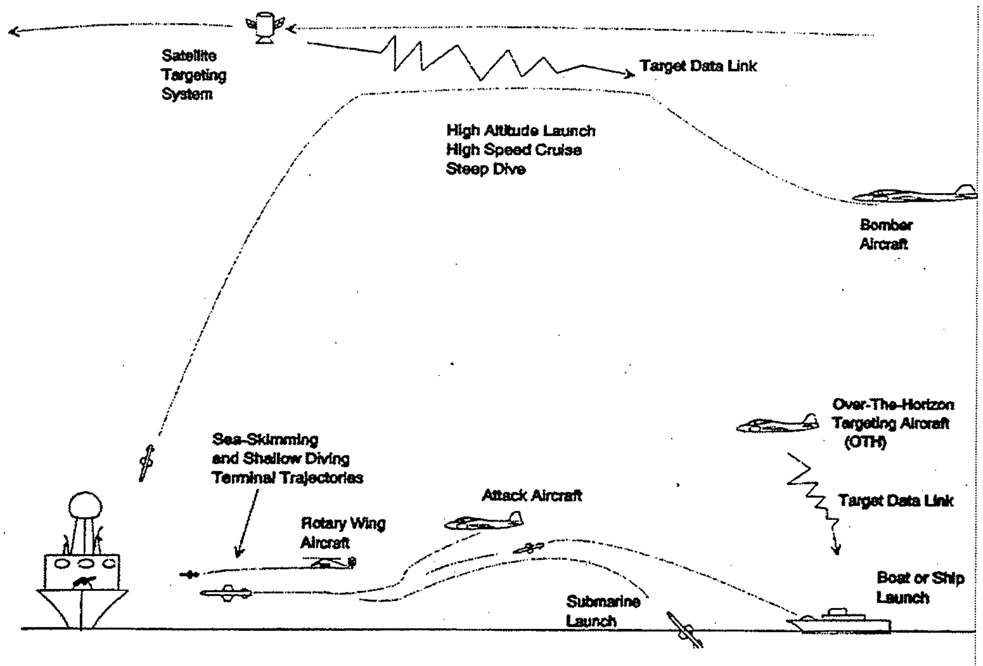


Figure 2. Delivery and targeting methods of ASMs. [Ref. 2: pp. 11]

B. ELEMENTS OF THE SSAD SYSTEM

The main purpose of the SSAD system is to protect ships from ASMs. A SSAD system uses hardkill and/or softkill defense methods to perform its mission. Hardkill defense methods encompass the classical kinematics kill, which destroys an ASM physically either by collision or by explosion. Whereas, softkill defense methods aim at the control and guidance subsystems of an anti-ship missile and divert it away from the ship through confusion, distraction, deception, or seduction.

This thesis focuses on a specific type of SSAD, which uses only hardkill defense methods with Surface-to-Air Missiles (SAMs). Softkill defense methods will have the same effectiveness regardless of which hardkill system is used. Hence, this thesis only models the hardkill defense methods. The SSAD system modeled for this thesis has the following elements:

- Surveillance systems
- Tracking sensors

- Fire Control System
- Launchers
- SAMs

1. Surveillance Systems

Success in the SSAD system depends on the ability to detect the incoming target as early as possible. The SSAD system must be aware of the incoming target in enough time to use its defenses. Early detection of the incoming target is the responsibility of the surveillance systems. Basically, there are three kinds of surveillance systems: radar, infrared (IR) sensors and optical sensors. This thesis models the radar as the surveillance system.

Radar is an acronym for Radio Detection and Ranging. It uses radio transmissions to collect information. Radio transmissions can be seen as analogous to light waves. They are sent out from the radar antenna and bounce back from any object in their path just as light waves would from a polished surface. Equally, just like light waves, the radio transmissions can be deflected, diffused or absorbed. Radar detects targets by reflected radio transmissions from the target, i.e., the echo. Two basic characteristics of the target can be obtained from its radar echo: metric characteristics and signature characteristics. Metric characteristics give the target location in terms of range and angular measurements and their derivatives. Signature characteristics provide insight into target identification. [Ref. 3: pp.1]

2. Tracking Sensors

Semi-active homing SAMs require a tracking sensor (illuminator) from the ship to illuminate the threat during the entire flight period. To do this, tracking sensors must first obtain threat information from a surveillance system. "Designation is the process of using information from one sensor to point another sensor in the direction of the target so the second, designated sensor, can quickly detect and acquire the target."[Ref. 2: pp. 50]

Second, tracking sensors will illuminate the threat by sending narrow beamwidth radio transmissions.

A tracking sensor can only illuminate one threat at a time and, depending on the air defense system, generally there will be from two to four illuminators onboard the ship. The number of tracking sensors onboard is an important constraint and it makes the assignment process of the tracker and the missile to counter the threat very critical. With increasing numbers of threats, the air defense system may face the possibility of saturation.

3. Fire Control System

The fire control system is the major coordinator of the SSAD. It estimates the threat's future position, provides aiming or pitchover values to the launcher, and assigns SAMs and tracking sensors to the related threats. To obtain an effective assignment, the fire control system, first, prioritizes threats according to the remaining time before they hit the ship. Then, it checks the following information, which represents the current status of the SSAD system:

- Characteristics and the number of available SAMs
- Characteristics and total number of available tracking sensors
- Firing Policy

Firing policy is an important tactical issue. This thesis models and analyzes two different firing policies: "Shoot-Look-Shoot" (S-L-S) and "Shoot-Shoot-Look" (S-S-L).

a) Shoot-Look-Shoot Firing Policy

In the S-L-S policy, the second missile is not fired until the first has intercepted the target, and the kill assessment process has indicated that the target has not been destroyed. With this policy, missiles are conserved at the cost of fewer opportunities to make the kill.

b) Shoot-Shoot-Look Firing Policy

In the S-S-L firing policy, two missiles are fired in a salvo before a kill assessment is made. With this policy a higher cumulative probability of kill, Pk, is achieved in the shortest possible time against a particular target. However, missiles may be expended unnecessarily using the S-S-L policy if the target is destroyed by the first missile, as happens in some given percentage of cases. The time separation between missiles in the salvo can be varied using the parameter t_{salvo}. Assuming that missiles are loaded and ready to fire, t_{salvo} is usually small. [Ref. 2: pp. 334]

4. Launchers

The task of the launcher is to carry and launch SAMs in response to orders given from the fire control system. Two types of launchers are commonly used in SSAD systems: deck-mounted launchers and vertical launchers. The main difference between these two types of launchers is in the aiming procedure. A deck-mounted launcher must be aimed in azimuth by a servo motor (an electrical motor) that receives pointing angles from the fire control system before it launches a SAM. On the other hand, a vertical launcher can engage all threats over any azimuths. After being vertically launched, the SAM pitches over along a preprogrammed or commanded azimuth until it reaches a designated elevation angle. Because of the pitchover movement, SAMs launched by a vertical launcher have longer minimum threat kill range than SAMs launched by a deck-mounted launcher.

5. Surface-to-Air Missiles (SAMs)

SAMs have longer intercept ranges than any other self-defense weapons. For this reason, they are the dominant weapons in hardkill defense. But their longer range increases the requirement for accuracy. For example, in order to be effective, depending on warhead characteristics and target vulnerability, SAM warheads must be designed to detonate within five to twenty meters of the target. [Ref. 2: pp.135] This fact shows the importance of the guidance system in SAM design.

a) Guidance Phases

Guidance is the process that brings the SAM and the threat together at the same point in space and at the same instant. [Ref. 2: pp. 135]

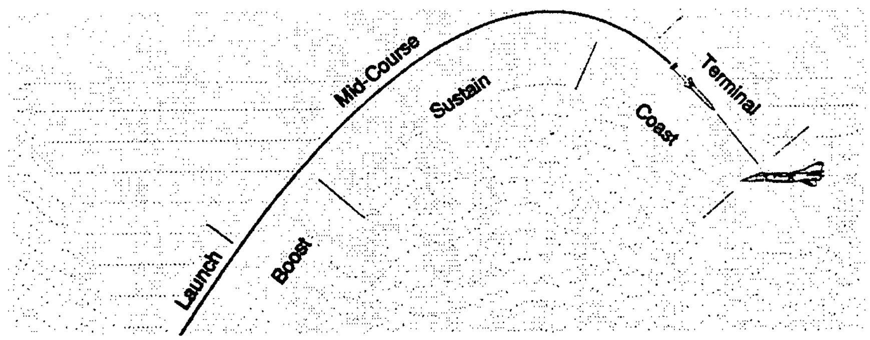


Figure 3. Guidance phases of SAMs. [Ref. 2: pp. 214]

As illustrated in Figure 3, three guidance phases are employed in SAMs: launch, mid-course, and terminal.

(1) Launch Phase. During this phase, the SAM is typically commanded to maintain a constant altitude or zero g level to allow speed and controllability to reach specified values. This phase usually takes no more than few seconds.

(2) Mid-Course Phase. This phase is employed in those larger SAMs that are designed for long-range intercepts. It is usually characterized by a ground station that uplinks acceleration commands to the missile based on separate target and SAM tracks. With this type of system, guidance commands can be programmed to optimize some aspect of SAM trajectory such as the intercept velocity, approach angle or range.

(3) Terminal Phase. This phase controls the SAM from the end of midcourse phase to the point where a direct hit or a near miss on the target occurs. [Ref.2: pp. 214]

b) Guidance Methods

Typical guidance methods in SAMs include command, beam rider, and homing. Each method is shown in the Figure 4 below.

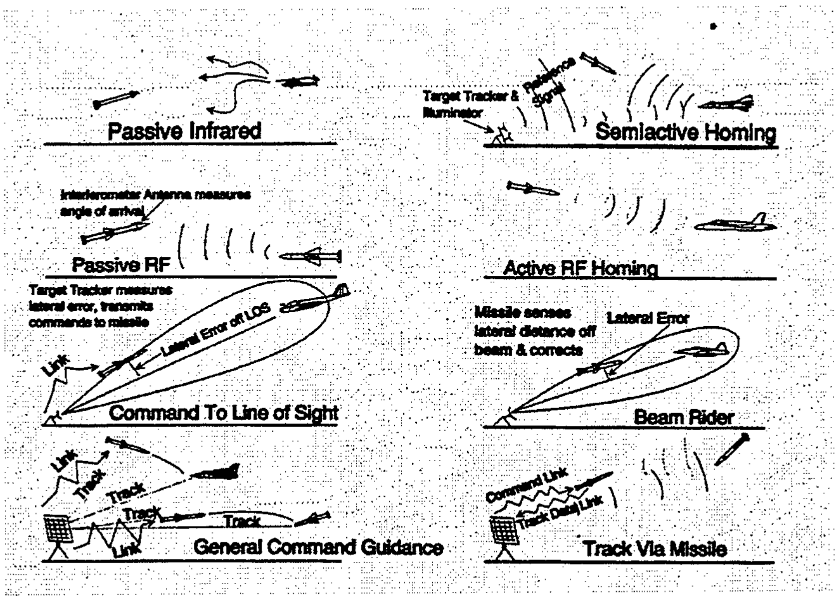


Figure 4. Some typical guidance implementations of SAMs. [Ref. 2: pp. 215]

(1) Command Guidance. Command guidance is based on ground computation of guidance commands, followed by transmission to the SAM via a data link. In this guidance, the tracking sensor measures the lateral error off line-of-sight (LOS) and transmits it to the SAM.

(2) Beam-Rider Guidance. Beam-rider guidance systems require that the SAM, sense its lateral displacement relative to the LOS between an active ground sensor and the threat. Guidance commands are then generated in the SAM to zero lateral error.

(3) Homing Guidance. Homing is the most common guidance method among SAMs. Homing missiles carry a tracking sensor, called a seeker. Depending on the characteristics of the seeker, there are four types of homing guidance: passive IR homing, passive radio frequency (RF) homing, semi-active homing, and active RF homing. Passive IR and RF homing guidance are based on passive tracking of the target's IR or RF emission. Semi-active homing guidance allows the SAM to track the target by receiving the reflected RF energy, which is originally emitted from the tracking sensor, from the threat. Active RF homing guidance first, emits the RF energy via its seeker. Then, it tracks the threat by receiving the reflection of this RF energy. [Ref. 4: pp. 18-23] This thesis models the active and semi-active RF homing guidance.

In the remainder of this chapter, the role of each element of SSAD will be explained with respect to SSAD system processes.

C. SSAD SYSTEM PROCESSES

A SSAD system is represented by the following processes:

- Detection (Search and Detection of ASMs)
- Control (Track ASMs and weapon assignment)
- Engagement (Fire the assigned weapons to the related ASMs)

Figure 5 illustrates the sub-level processes of each process.

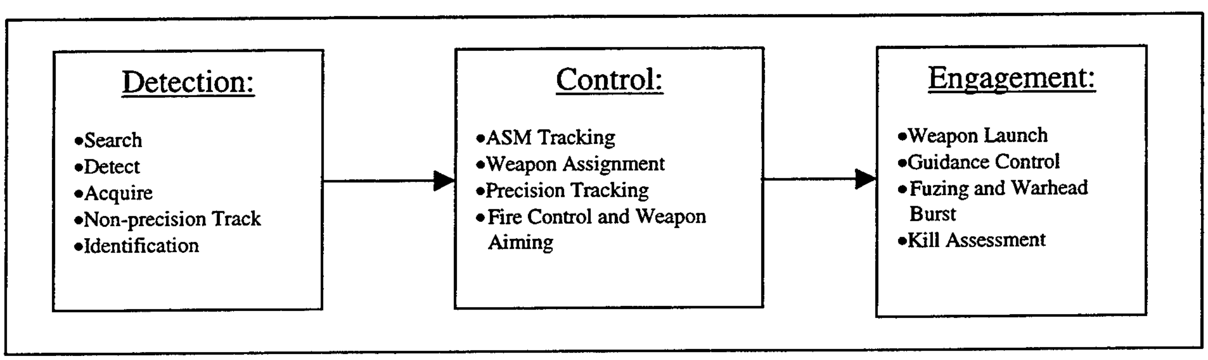


Figure 5. SSAD System Processes and Sub-level Processes

1. Detection Process

The detection process involves the search, detection, and identification of threats. It is associated with surveillance systems. It has the following sub-level processes: search, detect, acquire, non-precision track, and identification.

Search is the inspection of a given volume of space by a surveillance system. During the search process, if a target is sensed, detection occurs. Detection is a single event and it provides only limited information about the target, i.e., a detection has occurred. Acquisition refers to the repeated detection of a new target during several scans. It allows the surveillance system and operators to extract information about the target concerning its position, velocity, and perhaps intent. Non-precision tracking updates the target's position and velocity each time it appears in the surveillance system. Identification determines if the target is hostile by estimating future movements and analyzing electronic emissions of the target. [Ref. 2: pp. 39-48]

2. Control Process

Once a contact has been declared as hostile, the control process begins. This process is associated with tracking sensors and the fire control system. It involves the execution of the following sub-level processes: ASM tracking and weapon assignment, precision tracking, fire control, and weapon aiming.

Assignment is a coordination process. Its objective is to pair appropriate tracking sensors and weapons with the threats. In multiple threat environments, the assignment process becomes more critical because of the possibility of overkill or underkill. To obtain an effective assignment, the fire control system follows the assignment procedure mentioned in the fire control section of this chapter. Once the assignment process is executed, the precision track process begins. This process is associated with tracking sensors and refers to the generation of precision target position and velocity data that is used to control weapon aiming and guidance. Fire control and weapon aiming constitute the process of determining the direction to point a missile so that it will hit its target when fired. As a result of this process, the launcher orders are sent to the launcher. These orders consist of pointing angles for deck-mounted launchers and pitchover information for vertical launchers. The initial SSAD-Sim does not model tracking errors. This was deemed unnecessary for our present purposes. However, if another study requires that tracking errors be explicitly modeled, the modular design of SSAD-Sim makes this addition relatively easy.

3. Engagement Process

Engagement is the final process of the SSAD. The objective of this process is to fire the assigned weapons, and to inflict and assess damage on the threat. To fulfill this objective, this process uses the launchers and SAMs. This process involves the execution of the following sub-level processes: weapon launch, guidance control, fuzing and warhead burst, and kill assessment.

Once a weapon is assigned to a target, the launcher receives the launcher orders and launches the missile. After the missile is launched, the guidance control process begins to direct the SAM to the intercept point. At the intercept point, the fuzing and warhead burst process occurs. At that point, three types of damage mechanisms can be involved in destroying the target:

- SAMs directly hit the target.
- Fragments ejected by warheads carried by SAMs hit the target.
- Pressure from warhead blast is applied to the target skin.

The application of these mechanisms does not guarantee that the target will be killed. Indeed, it may not even be damaged. [Ref. 1: pp.35] Therefore, for each target a kill probability (P_k) may be assigned. For different firing policies, assuming that SAMs kill targets independently, P_k is determined as follows:

a) n Missiles are Allocated against One Target Case:

$$P_k = [1-(1-P_{k_1})^n]$$

where, P_k = probability of killing the target

P_{k_1} = probability of killing the target by one launched missile

n = missiles allocated to target

b) n Missiles Allocated against the First target and N-n Missiles are Allocated to the Second Target Case:

$$P_k = [1-(1-P_{k_1})^n]*[1-(1-P_{k_2})^{(N-n)}]$$

where, P_k = probability of killing all targets

P_{k_1} = probability of killing the first target by one launched missile

P_{k_2} = probability of killing the second target by one launched missile

n = missiles allocated to first target

N-n = missiles allocated to second target ,

$n \leq N$ and $N \leq$ all available missiles

c) n_i Missiles are Allocated against ith Target case:

$$P_k = [1-(1-P_{k_1})^{n_1}]*....*[1-(1-P_{k_t})^{n_t}]$$

where, P_k = probability of killing all targets

P_{k_1} = probability of killing the first target by one launched missile

n_i = missiles allocated to ith target

$n_1+..+n_t \leq$ all available missiles

$n \leq N$

Before classifying a target as destroyed or not destroyed, a kill assessment must be made; this requires some time, labeled t_{ka}, because it takes time to determine if the target is destroyed and to determine if another shot will achieve an intercept within the effective range of the weapon. If it is determined that the target is not destroyed after a t_{ka} duration, the secondary kill assessment process is repeated until the intercept falls outside the effective weapon range.

III. SSAD-SIMULATION

A. OVERVIEW

In order to represent the Ship Self Air Defense (SSAD) system described in Chapter II, this thesis develops a prototype Monte-Carlo discrete event SSAD simulation model, called SSAD-Sim (See Appendix A for the goodness of fit tests of random numbers used in SSAD-Sim simulation). SSAD-Sim is a platform independent, object-oriented, modular and expandable simulation tool. Within the limits drawn by its assumptions, it can be used to fulfill the following objectives:

- To assist decision authorities to select the best SSAD system.
- To assess suitable tactics for different threat environments.
- To determine the necessary modifications to SSAD systems, in conjunction with developments in threat characteristics.
- To provide a training opportunity for the users of SSAD systems.

The Java programming language and the packages, Simkit and Modkit, were used to develop SSAD-Sim. The Java programming language was selected because of the following reasons:

- Java programs run on a wide variety of hardware platforms (platform independence).

  In other programming languages, the compiler creates platform specific machine language code. With Java, the compiler creates Java byte-code. Java byte-code is executed by a program called Java virtual machine. A Java application runs on every machine for which a Java virtual machine has been implemented.

- Java is a completely object-oriented programming language.

  Object Oriented Programming (OOP) is one of the dominant programming paradigms. In OOP, large projects are separated into manageable objects. When needed, these objects can easily be re-used and modified.

Simkit and Modkit packages were selected in order to develop discrete event simulations. Both packages were written Java. Simkit was developed by Lt. Kirk Stork and Arnold Buss Phd., for constructing discrete event simulations using an entity based approach to modeling and simulation. Modkit was recently developed by Maj. Arent Arntzen, Norwegian Air Force, as a tool for modular component-based modeling. The component is an application independent object that represents a real world entity. Components have the following advantages when used in discrete event simulation models:

- Components can be used in multiple applications without any change.
- With a slight modification, the functionality and the task of components can be significantly changed.
- Components can be connected to each other easily.

These features are extremely valuable for exploratory analysis and a meaningful addition to the SSAD decision making process. The analysis environment is one in which answers are needed quickly; therefore, it is usually impossible to build a tool in the allowable time. Consequently, analysts need "ready" tools that they can quickly modify to meet the inevitably unique characteristics of their analyses with sufficient detail.

The rest of this chapter presents a description of SSAD-Sim including: (i) a summary of a single execution SSAD-Sim simulation, (ii) modeling and simulation assumptions, (iii) component descriptions, and (iv) creation of the database.

B. SSAD-SIM SIMULATION WITH A SINGLE EXECUTION

A single execution of SSAD-Sim simulation can be summarized as follows. When the simulation starts, threats begin their movement toward the ship. The detection process begins when threats enter the surveillance system's maximum detection range. If threats are detected, their threat information is transferred to the fire control system. In the fire control system, each threat is prioritized, in order, from earliest arrival time to latest arrival time to the ship. The SAM assignment process is then initiated against the threat with the highest priority. After SAMs are assigned to the threats, launch information is sent to the launcher. A launch delay inserted to simulate, as soon as the launch delay time is over, the SAMs are launched and they begin their flight to the ASMs. The SAM flight is over at a precalculated hit time with the threat ASM. At the hit time, the SAM either hits or misses the threat with a given kill probability. If the threat is killed, the threat is unable to hit the ship and it is removed from the simulation. Whereas, if the threat is missed, after a kill assessment delay, the SAM assignment procedure is repeated with the next missile.

SSAD-Sim simulation ends if one of the following conditions hold:

- One of the threats hits the ship.
- All of the threats are killed before they hit the ship.

A detailed event graph of the execution of SSAD-Sim simulation is provided in Appendix B.

C. ASSUMPTIONS MADE IN SSAD-SIM

The purpose of the assumptions in SSAD-Sim is to model only the critical parameters that are important to the Turkish Navy's general SSAD system requirements. Second order aspects of the SSAD system are omitted. The following assumptions are incorporated into the SSAD-Sim model:

1. General Assumptions

- Within the scope of analytical OR techniques, known physical parameters are used for the calculations.
- Environmental Conditions (Weather, sea state… etc.) are not treated explicitly.
- Operator errors and differences between operators are not modeled.
- For simplicity, "Soft Kill" counter measure systems (decoys, chaff, and radar jamming devices) are not explicitly modeled.

2. Ship Assumptions

- The speed of the ship is slow compared with the speed of the missiles. Thus, ship motion is not modeled; the ship is assumed stationary, and stays at the (0,0,0) coordinate during the simulation.
- Ship superstructures are not addressed.

3. Surveillance System Assumptions

- Since the analysis focuses on different missile performances and firing policies, radar is modeled as the only surveillance system.
- The Radar uses a scanning search model.
- The Radar uses fully automatic systems to detect and acquire threats.

4. Launcher Assumptions

- Launch is automatically fired by the fire control system.
- Launcher positioning errors are ignored, because unless launcher-positioning errors are very large their effects on missile accuracy are negligible.
- Each launcher is assumed to launch only one type of missile.

5. Tracking Sensor Assumptions

- Each tracking sensor can only illuminate one threat.

6. Surface-to-Air Missile Assumptions

- The SAMs are assumed to move linearly. Acceleration and nonlinear movement are not modeled.
- Only one type of SAM can be used against each threat.
- Semi-active homing SAMs require an all-the-way illuminated threat. In addition, active SAMs use their seekers to track the threat.

7. Threat Assumptions

- The threat is defined as incoming anti-ship missiles. No aircraft are used as a threat.
- The threat has constant velocity and it is aimed directly at the ship.
- The threat is scripted, instead of reactive. That is, a scripted threat flies a pre-set path that does not vary with changing circumstances. Whereas, A reactive threat modifies its flight path and operating characteristics according to its intended threat.

D. GENERAL DESCRIPTIONS OF SSAD-SIM COMPONENTS

SSAD-Sim consists of nine components, as diagramed in Figure 6. Seven of components simulate the elements of the SSAD system, and are called *system* components. Two of the components are called *mediator* components and they coordinate the information flow between related system components.

The seven system components consist of the following:

- The BasicSensor component—simulates the surveillance system.
- The FireControl component and the FiringPolicy components—simulate the fire control system.
- The Tracker component—simulates the tracker.
- The Launcher component—simulates the launcher.
- The OutgoingMissile component—simulates the SAM.
- The TargetMover component—simulates the threat.

The two mediator components are as follows:

- The MissileTargetMediator component—coordinates between the OutgoingMissile and the TargetMover components.
- The SensorMoverMediator component—coordinates between the TargetMover and the BasicSensor components.

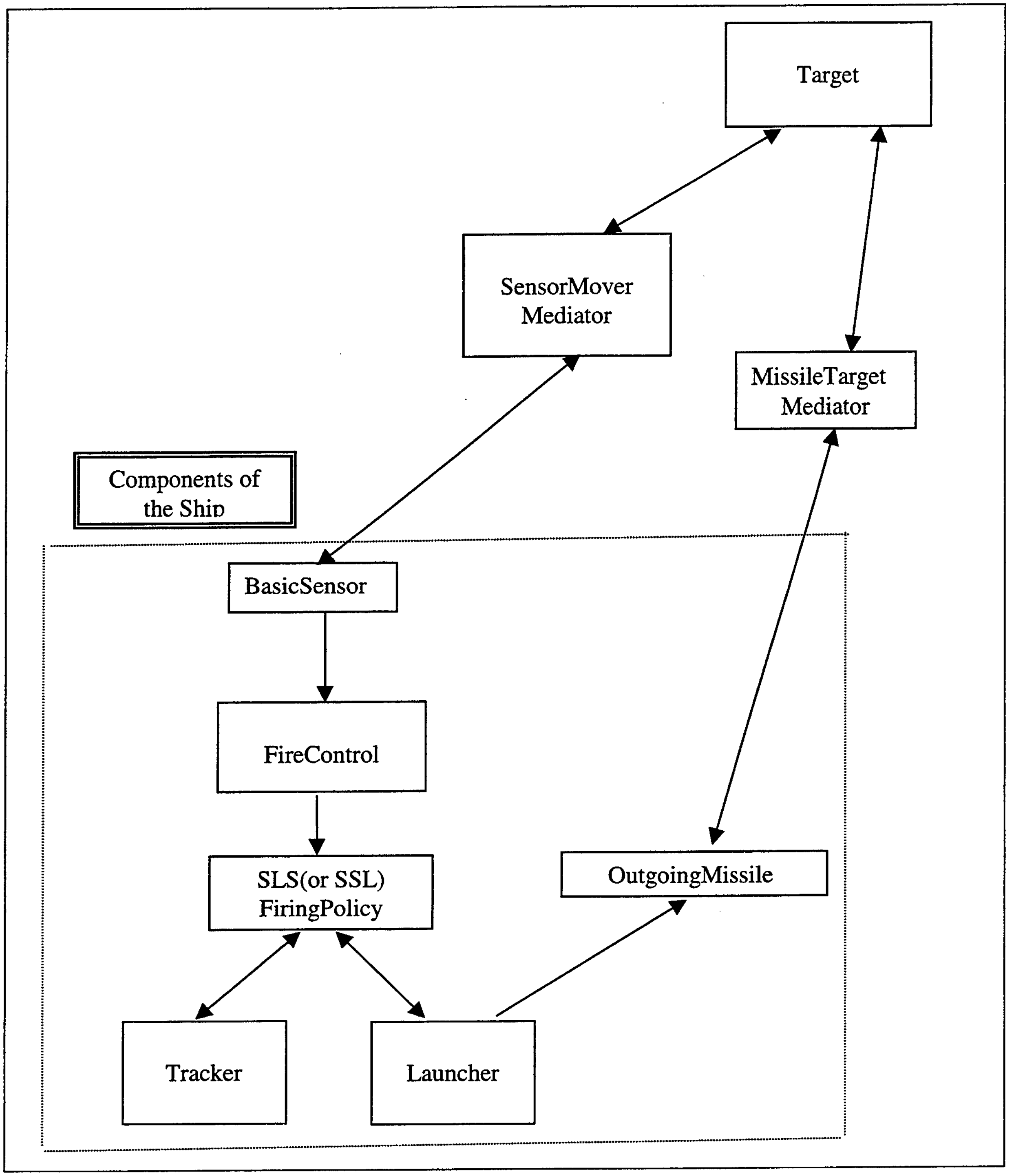


Figure 6. Component Map of SSAD-Sim. (In this graph, boxes show components and arrows show the information transformation directions between components.)

1. BasicSensor Component

The BasicSensor component uses a discrete-looking sensor approach to simulate the surveillance system. The main task of this component is to provide the Probability of detection (P_d) to the SensorMoverMediator component. To provide P_d, the BasicSensor needs two inputs: A table of P_d as a function of range and the distance to the threat. The P_d versus range tables is entered in the model while creating the BasicSensor component. When modeling the Pd data points, characteristics of the target, surveillance system, and the environment should be considered. Because these characteristics affect sensor performance, the distance from the ship to the target is calculated by the SensorMoverMediator component at each discrete looking time and then input to the BasicSensor.

Calculation of the P_d is made in two steps. First, the distance is entered into the BasicSensor by the SensorMoverMediator. Second, P_d is calculated by linearly interpolating P_d versus range points. However, if the distance is longer than the maximum detection range or shorter than the minimum detection range of the surveillance system, the P_d is zero.

2. FireControl Component

The FireControl component is the main coordinator of the weapon assignment process. Once a target is detected by the BasicSensor component, it is then transferred to the FireControl component. After a recognition delay, which may be caused by the operator decision delay etc., the target is put into a priority queue (ShortestTime class). The targets are prioritized, in order, from earliest hit time to latest hit time. The hit time is calculated by dividing the distance between the target and the ship by the current target speed.

In the coordination of the weapon assignment, the FireControl selects the target having the highest priority and then sends it to the selected FiringPolicy (Shoot-Look-Shoot or Shoot-Shoot-Look) component.

3. FiringPolicy Components

There are two FiringPolicy components in SSAD-Sim, the Shoot-Look-Shoot-FiringPolicy component and the Shoot-Shoot-Look-FiringPolicy component. The components have similar design; but, the SLSFiringPolicy component initially assigns one outgoing missile to the incoming target while the SSLFiringPolicy component assigns two. One component for each firing policy makes SSAD-Sim more flexible. In reality, there are other firing policies and potential future firing policies that may be introduced. Whenever a new firing policy is needed, SSAD-Sim can easily be modified by creating and adding the new firing policy component.

After the target is sent from the FireControl component to the FiringPolicy component, the weapon assignment process continues as follows:

First, the outgoing missile hit time for each outgoing missile is calculated by using the formula given below and put into an array:

$$T_H = \frac{D}{V_T + V_O} + t_{salvo}$$

Where, T_H = outgoing missile hit time
D = distance between the ship and the target
V_T = target speed
V_O = outgoing missile speed
t_{salvo} = salvo delay time
(for active outgoing missiles)
= launch delay time+tracker slew delay time
(for semi-active outgoing missiles)

Second, the location of the target at the hit time, which depends on the calculated hit times for each kind of missile, is determined. Then, by using the location of the target at each hit time, the missile hit distances for each missile are calculated and put into an array. During these calculations, the FiringPolicy component also checks the availability of each outgoing missile. For the semi-active outgoing missiles, the FiringPolicy component also checks the availability of the trackers. If the incoming missile cannot be countered, either by a lack of outgoing missiles or trackers, the hit distance is assigned a zero. However, if one tracker becomes available before the incoming missile (having the zero hit distance) hits the ship, the hit distance calculation is repeated for this incoming missile.

Finally, after these calculations are made, the outgoing missile having the longest hit distance is selected to launch. Four-dimensional outgoing missile destination information (x, y, z coordinates and t, the hit time) is sent to the related launcher.

4. Tracker Component

The main function of the Tracker component is to provide the available number of trackers and the tracker slew delay time information to the FiringPolicy component.

In the Tracker component, the available number of trackers is updated in the following way. After the assignment of a semi-active missile, the available number of trackers is decreased by one. After a target is killed, the available number of trackers is increased by one after a kill assessment delay.

5. Launcher Component

The Launcher component does the following: 1) assigns outgoing missile parameters for the OutgoingMissile component, 2) provides the launch delay time and the number of available outgoing missiles to the FiringPolicy component, 3) launches the assigned outgoing missiles, and 4) creates the related MissileTargetMediator components.

Each launcher carries only one type of OutgoingMissile, with a user specified number. These OutgoingMissile components are created from one OutgoingMissile component using java.lang.class and java.lang.constructor classes. The total number of OutgoingMissile components cannot exceed the outgoing missile capacity of the Launcher component.

After an outgoing missile is assigned to launch by the FiringPolicy component, a four-dimensional outgoing missile destination is sent to the related Launcher component.

Then the destination of the related OutgoingMissile is set in the Launcher component and the related MissileTargetMediator component is created.

6. OutgoingMissile Component

The OutgoingMissile component simulates a SAM moving with constant velocity. It can represent either an active or a semi-active SAM. Its function and the relationships between other components can be summarized as follows.

After destination point information is sent to the OutgoingMissile component by the Launcher component, the OutgoingMissile component begins its movement towards this destination point. At the hit time, the MissileTargetMediator component asks the OutgoingMissile component whether or not it killed the target. To answer this question, the OutgoingMissile component needs the following information: Probability of kill (P_k), kill radius, and the distance to the target. P_k and kill radius information is entered while the OutgoingMissile component is created. On the other hand, distance to the target is calculated by the MissileTargetMediator component and it is sent to the OutgoingMissile component. Once each component has the required information, the MissileTargetMediator component first checks whether the distance is smaller than or equal to the kill radius. If the distance is smaller than the kill radius, a uniform random number is generated in the [0,1] interval. If the uniform random number is less than or equal to the P_k the target is killed. However, if the distance is larger than the kill radius it misses the target. In the analysis in Chapter IV and Chapter V, miss distance is not used. Instead, direct intercepts are assumed; however, this feature is included to facilitate future enrichments.

7. MissileTargetMediator Component

The MissileTargetMediator component is created in the Launcher component as explained in the Launcher component section. This component coordinates the information flow between the Target component and the OutgoingMissile component. At the hit time, it first calculates the distance between the OutgoingMissile and the Target component then enters this distance into the OutgoingMissile component and asks the

OutgoingMissile component whether or not it kills the Target. Then, if the Target is killed, the number of tracked targets in the BasicSensor component is decreased by one and the FireControl component is informed about the killed target. Whereas, if the Target is missed the SAM assignment procedure is repeated with the next missile by the FireControl component.

8. Target Component

The Target component simulates a constant velocity moving incoming missile. As in the OutgoingMissile component, it has a kill radius. If the distance between the target and the ship is less than or equal to the kill radius, the ship is destroyed and the simulation is ended.

9. SensorMoverMediator Component

The SensorMoverMediator component coordinates the information flow between the BasicSensor component and the Target component. It calculates the hit time of the target and informs the Target component at the hit time. It also calculates the target's time of entry into the surveillance system's maximum detection range by calculating Line-of-Sight (LOS). After the target has entered to the surveillance system's maximum detection range the SensorMoverMediator component calculates the distance between the target and the ship at each discrete looking time and enters this distance into the BasicSensor component. Then, it asks the BasicSensor component if it has detected the target. This procedure continues until the BasicSensor component detects the target.

E. THE INPUT AND OUTPUT PARAMETERS

1. The Input Parameters

For each individual element of the SSAD, the following input parameters can be entered to SSAD-Sim:

a) Surveillance System

- Maximum detection range
- Minimum detection range
- Maximum number of targets can be tracked
- Probability of detection versus range points
- Discrete looking time
- Antenna height

b) Fire Control System

- Firing policy
- Recognition delay

c) Tracker

- Total number of trackers onboard
- Tracker slew delay
- Maximum range of the tracker

d) Launcher

- Total number of SAMs in the launcher
- Type of the SAM
- The launch delay
- The salvo delay

e) SAM

- Maximum kill range
- Minimum kill range
- Maximum speed
- Kill radius
- Guide status (Active or Semi-active)
- Probability of kill

f) Threat

- Flight pattern
- Maximum speed
- Kill radius

2. Output parameters

For each simulation run, SSAD-Sim provides an output file. This output file gives the detailed information about each iteration of a simulation run. At the end of each simulation run the following output parameters are calculated and written into this output file.

- Probability of no leakers
- Number of killed targets
- Number of expended SAMs
- Maximum kill distance
- Minimum kill distance
- Average kill distance

A representative output file is attached in the Appendix C.

F. CREATING THE SSAD-SIMULATION DATABASE

In order to be used in the scenarios in the next chapter, the database of SSAD-Sim is created. The database of SSAD-Sim provides nominal values to parameters of each SSAD system element. In creation of the SSAD-Sim database, unclassified sources like the U.S. Navy home page, the Raytheon Company and the Aster company press releases, and Jane's missile systems are used. In the remainder of this chapter, the database values of SSAD-Sim are given.

1. The Threat, ASM

- Maximum speed: 350 meters/sec.
- Cruise altitude: 5 meters

2. SSAD System 1 (Semi-active SSAD)

a) Surveillance System

- Single-scan probability of detection (Pd) versus kill points are presented in the Table 1:

Range (in Nautical Mile)	Pd
12 or less	1.000
13	0.900
14	0.850
16	0.800
17	0.600
18	0.500
19	0.400
20	0.200
21	0.092
22	0.080

Table 1. Pd. versus. kill points of the Surveillance System

- Maximum detection range: 22 Nautical Mile (NM)
- Minimum detection range: 0 NM
- Maximum number of targets that can be tracked: 10
- Discrete looking time: 4 seconds
- Antenna height: 60 feet

b) Fire Control System

- Firing Policy: Shoot-Look-Shoot (S-L-S) and Shoot-Shoot-Look (S-S-L).

- Recognition delay: Normally distributed with a mean of 3 seconds and a standard deviation of 0.3 seconds.

c) Tracker

- Total number of trackers: 2
- Tracker slew delay: 6 seconds

d) SAM 1

- Maximum kill range: 6.9 NM
- Minimum kill range: 0
- Maximum speed: 44.3 NM/minute
- Kill radius: 0
- Guidance: semi-active
- Probability of kill: 0.6-0.8

e) Launcher

- Total number of SAMs in launcher: 20
- Type of SAM: SAM 1
- The launch delay: 6 seconds
- The salvo delay: 2 seconds

3. SSAD System 2 (Active SSAD)

a) Surveillance System

Same as given in SSAD system 1.

b) Fire Control System

Same as given in SSAD system 1

c) Tracker

Same as given in SSAD system 1

d) SAM 2

- Maximum kill range: 10 NM
- Minimum kill range: 0 NM
- Maximum speed: 36.65 NM/minute
- Kill radius: 0 ft.
- Guidance: active
- Probability of kill: 0.6-0.8

e) Launcher

- Total number of SAMs in launcher: 20
- Type of SAM: SAM 2
- The launch delay: 6 seconds
- The salvo delay: 2 seconds

IV. SSAD SYSTEM EFFECTIVENESS ANALYSIS

This chapter presents typical analytical calculations that can be obtained from the initial Ship Self Air Defense (SSAD) simulation, developed for this thesis. The example simulation analysis described in this chapter pertains to a hypothetical system effectiveness analysis of a SSAD system. The analysis is based on the following representative SSAD system selection problem.

Decision makers of the Turkish Navy have to decide on the best SSAD system available for installation on their newly built frigates for the 21st century. Two candidate SSAD systems are introduced by two competitive companies. Company A proposes SSAD system 1 (a semi-active SSAD system) and Company B proposes SSAD system 2 (an active SSAD system). These systems have already been discussed in the SSAD-Sim database in the previous chapter. Each SSAD system can use either Shoot-Look-Shoot (S-L-S) or Shoot–Shoot-Look (S-S-L) firing policies. Decision makers expect to judge the effectiveness of the two competitive SSAD systems in the following stressing, yet plausible, scenarios:

- Scenario 1: A ship tries to defend itself by using its SSAD system against three approaching ASMs, which arrive with a six-second spacing.
- Scenario 2: A ship tries to defend itself by using its SSAD system against two raids of two ASMs each. The first ASMs of each raid arrive the ship simultaneously. The second ASMs of each raid arrive the ship six seconds later.

In order to select the most effective SSAD system, decision makers must evaluate the following:

- Which SSAD system is more effective for each threat environment?
- What is the best firing policy for each candidate SSAD system?

These questions can be answered by analyzing the data of each scenario. The best way to gather this kind of data is through simulation. Since the effectiveness may depend on numerous factors the simulation will investigate many cases. In total, to support this analysis, the SSAD-Sim was run over 25,000 times. SSAD-Sim can easily provide the necessary data by simulating these two scenarios. Additionally, possible "What if" questions can easily be answered by changing the input values of SSAD-Sim simulation. Moreover, since SSAD-Sim is a component-based modular and expendable simulation tool, possible design modifications on SSAD systems can easily be evaluated on SSAD-Sim simulation by modifying or changing SSAD-Sim components.

To answer these questions, the following methodology will be used. First, Measures Of Effectiveness (MOEs) are determined. Second, representative scenarios are set up and the SSAD-Sim simulation runs are conducted. Third, the SSAD-Sim simulation results are analyzed and evaluated with reference to the MOEs. Fourth, sensitivity runs are made to investigate the robustness of the results.

A. MEASURES OF EFFECTIVENESS

The mission requirement of a SSAD system is to kill all incoming threats before they hit the ship. If a SSAD system cannot kill one or more of the incoming threats, it has failed. Threats that cannot be killed by the SSAD system are called leakers. In order to compare different SSAD systems, the probability of no leakers ($P_{noleakers}$) is used as the primary MOE. The SSAD system with a higher probability of no leakers is considered to be more effective than the SSAD system with a lower probability of no leakers.

If there is no significant difference between the probability of no leakers, the following intermediate MOEs are used to compare the two SSAD systems.

- Intermediate MOE 1 - Average number of expended SAMs.

  The fewer expended SAMs indicate better performing SSAD system.

- Intermediate MOE 2 - Average kill range of the threat.

  A longer kill range indicates a better performing SSAD system.

B. COMPARATIVE ANALYSIS

In order to determine the better firing policy or SSAD system, all MOEs will be compared by using two-sample tests for large sample sizes. The primary MOE, i.e., $P_{noleakers}$, will be compared by using two-sample tests for proportions. The intermediate MOEs will be compared by using two-sample tests for means. In the comparison of MOEs the following hypotheses will be used.

a) Hypotheses

H_0 = At the selected confidence level, there is no difference between the $P_{noleakers}$ (or means e.g., the average kill range) provided by both firing policies

H_A = At the selected confidence level, $P_{noleakers}$ (or mean) provided by one firing policy is better than the $P_{noleakers}$ (or mean) provided by the other firing policy

b) Confidence Level

Since for this kind of studies 0.05 type I error is considered as acceptable, 95% Confidence level is used.

c) Test Statistics

- Test statistics for the two-sample test for proportions.

This test statistics will be used to evaluate the main MOE.

$$Z-value=\frac{\hat{p}_1-\hat{p}_2}{\sqrt{pq\left(\frac{1}{m}+\frac{1}{n}\right)}}$$

[Ref. 5 pp: 376]

where, $\hat{p}_1$ = the bigger probability of no leakers

$\hat{p}_2$ = the smaller probability of no leakers

x = the total number of successes (i.e., no leakers for the ship) of sample 1

y = the total number of successes (i.e., no leakers for the ship) of sample 2

m = the total number of trials of sample 1

n = the total number of trials of sample 2

$$p = \frac{x+y}{m+n}$$

$$q = 1 - p$$

- Test statistics for two sample tests for means

  This test statistics will be used to compare the intermediate MOEs.

$$Z - value = \frac{\left(\overline{X} - \overline{Y}\right)}{\sqrt{\frac{s_1^2}{m} + \frac{s_2^2}{n}}}$$

[Ref. 5: pp. 352]

where, $\overline{X}$ - $\overline{Y}$ = the difference between the corresponding sample means

S_1 and S_2 = the corresponding sample standard deviations

m = the total number of trials of sample 1

n = the total number of trials of sample 2

Once the Z-value is determined by using the formulas above, the related P-value will be calculated by using the following formula:

P-value=1-Φ (Z-value)

Where, Φ *(z)* is the area under the standard normal distribution density function.

d) Decision Rule

Reject the null hypothesis if the P-value is less than or equal to the acceptable type I error (α).

Detailed analysis of each scenario is tabulated in Appendix E.

C. SIMULATION OF THE SCENARIOS BY USING THE SSAD-SIM

This thesis uses the following general approach to simulate the scenarios. For each SSAD system, the active SSAD and the semi-active SSAD system, both Shoot-Look-Shoot (S-L-S) and Shoot-Shoot-Look (S-S-L) firing policies are simulated. A total of four simulation runs are conducted. Thus, four different combinations of firing policies and SSAD systems are simulated as shown in Table 2.

Simulations	SSAD System Simulated	Firing Policy Simulated
Simulation 1	Active	S-L-S
Simulation 2	Active	S-S-L
Simulation 3	Semi-active	S-L-S
Simulation 4	Semi-active	S-S-L

Table 2 Simulation combinations

For each of the simulations in Table 2, a total of 400 runs are made with different random numbers generated starting at a SAM P_{kill} value of 0.6. The SAM P_{kill} value is increased by 0.05 and another 400 runs are made. This process is repeated until the SAM P_{kill} value reaches 0.8. This selected range of SAM P_{kill}, from 0.6 to 0.8, corresponds to the typical ranges of SAM P_{kill}. Thus, a total of 2000 runs of Simulation 1 (Active SSAD and S-L-S firing policy) are conducted. The same number of runs are similarly repeated for the other three simulation combinations.

The number of runs needed were determined by using the following formula.

$$n \geq \frac{Z_{\alpha/2}^{2}}{4d^{2}}$$

[Ref. 6: pp. 281]

The formula above gives the smallest number of runs (n) that will guarantee that the estimated probability ($P_{noleakers}$) will be within some specified tolerance d of the true probability ($P_{noleakers}$).

In order to find estimated $P_{noleakers}$ within 0.05 of the true $P_{noleakers}$, the smallest number of runs is calculated to be 384.12. This thesis uses 400 runs to find an estimated $P_{noleakers}$. Thus, the author decided to use 400 runs as the base case for the purpose of this research effort.

Once the simulation runs are conducted, the detailed simulation results are written into a selected output file along with a summary. (See Appendix D for summary simulation results of all scenarios)

D. SCENARIO 1

In order to evaluate the effectiveness of SSAD systems in a typical threat environment, the first scenario selected is a typical one for the ship. Scenario 1 can be summarized as follows. Three ASMs approach a single ship from the North flying at a cruise altitude of five meters. The distance between the ship and the launch point of the ASMs is 22.8 Nautical Mile (NM). The time interval between the arrival of each ASM to the ship is 6 seconds. Figure 7 illustrates a representative diagram of Scenario 1.

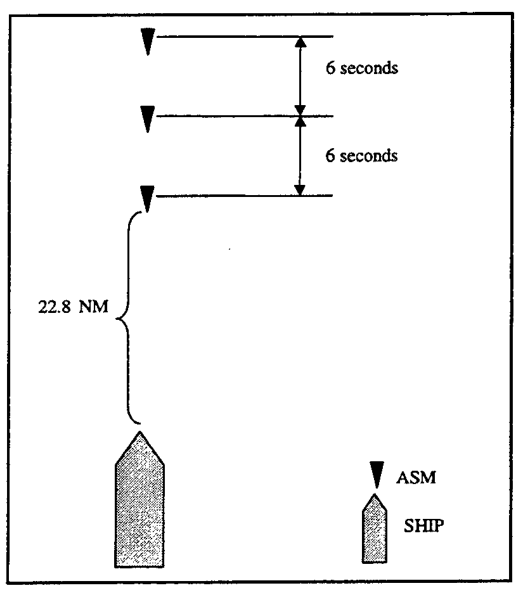


Figure 7. Representative Diagram of Scenario 1.

E. COMPARATIVE ANALYSES FOR SCENARIO 1

In this analysis, both the active and the semi-active SSAD systems are evaluated with a full SAM load out of 20 SAMs. Additionally, the semi-active SSAD system will be evaluated with two trackers having six-second tracker slew delays.

1. Comparative Analysis for the Primary MOE (Probability of No Leakers)

Figure 8 illustrates the probability of no leakers versus SAM P_{kill} values for the active and the semi-active SSAD systems as a function of firing policies for scenario 1.

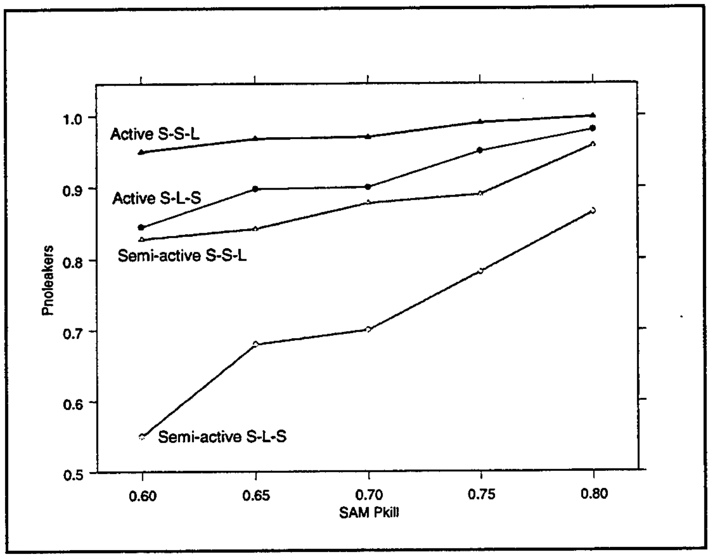


Figure 8. Probability of No Leakers ($P_{noleakers}$) versus SAM P_{kill} Values of the Active and the Semi-active SSAD Systems for Scenario 1.

Figure 8 shows that at all SAM P_{kill} levels the active SSAD system provides significantly higher $P_{noleakers}$ values than the semi-active SSAD system. The difference between $P_{noleakers}$ values provided by the active and the semi-active S-S-L policies varies from 0.04 to 0.126. Whereas, the same distance for the active and the semi-active S-L-S policies varies from 0.115 to 0.295.

Additionally, at all SAM P_{kill} levels, for both the active and the semi-active SSAD systems, the S-S-L firing policy provides higher $P_{noleakers}$ values than the S-L-S firing policy. The difference between $P_{noleakers}$ values provided by each firing policy decreases as SAM P_{kill} increases. These differences vary from 0.093 to 0.278. for the semi-active SSAD system and from 0.018 to 0.105 for the active SSAD system.

Figure 8 also shows that it takes a 0.8 SAM P_{kill} level for the semi-active S-L-S firing policy to be as effective as the semi-active S-S-L firing policy at a 0.6 SAM P_{kill} level. (See Table E.1. and Table E.2. for detailed statistical analysis.)

2. Comparative Analysis for the Intermediate MOEs

a) Comparative Analysis for average number of expended SAMs

Figure 9 illustrates average number of expended SAMs versus SAM P_{kill} values of the active and the semi-active SSAD systems for scenario 1.

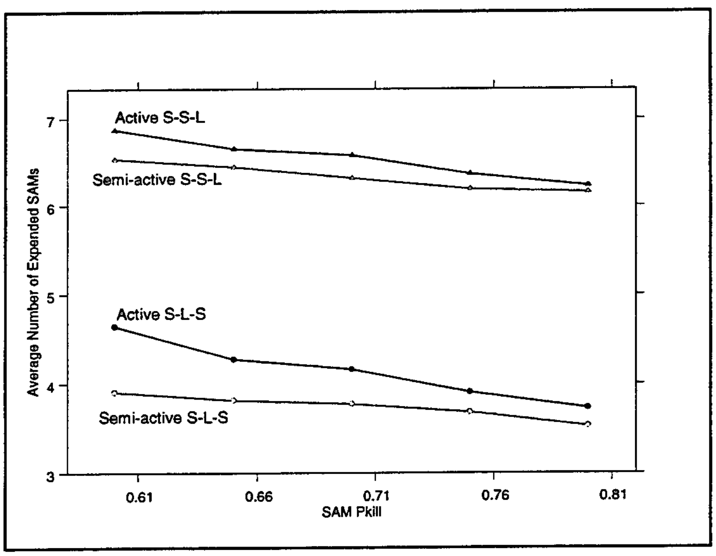


Figure 9. Average Number of Expended SAMs versus SAM P_{kill} Values of the Active and the Semi-active SSAD Systems for Scenario 1.

Figure 9 shows that for both SSAD systems, at all SAM P_{kill} levels the S-S-L firing policy expends over two more SAMs than the S-L-S firing policy. For the semi-active SSAD system, the difference between average number of expended SAM values provided by each firing policy is approximately 2.6 at all SAM P_{kill} levels. Whereas, for the active SSAD system, this difference increases from 2.22 to 2.49 as SAM P_{kill} value increases. (See Table E.3. and Table E.4. for detailed statistical analysis.)

b) Comparative Analysis for average kill range of threats

Figure 10 illustrates the average threat kill range versus SAM P_{kill} values of the active and the semi-active SSAD systems for scenario 1.

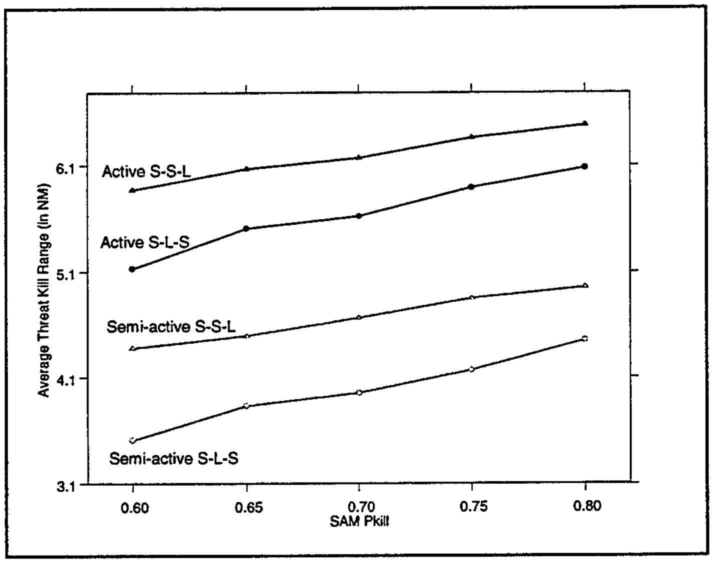


Figure 10. Average threat kill range versus SAM P_{kill} values of the Active and the Semi-active SSAD Systems for Scenario 1.

Figure 10 shows that for both SSAD systems, at all SAM P_{kill} levels the S-S-L firing policy kills threats at a longer range than the S-L-S firing policy. For the semi-active SSAD system, the difference between average threat kill ranges with respect to firing policies varies from 0.5 NM to 0.87 NM. Whereas, for the active SSAD system, this difference varies from 0.395 NM to 0.745 NM. (See Table E.5. and Table E.6. for detailed statistical analysis.)

3. Summary of the comparative analyses of MOEs for Scenario 1

Recall that in scenario 1, the ship has a 20 SAM load out and tries to defend itself against three approaching ASMs with a six-second time interval between each other. The

SSAD-Sim simulation results and comparative analysis results for scenario 1 can be summarized as follows.

- The active SSAD system provides higher $P_{noleakers}$ values than the semi-active SSAD system. The difference between $P_{noleakers}$ values provided by active and the semi-active S-S-L policies varies from 0.04 to 0.126. Whereas, the same distance for the active and the semi-active S-L-S policies varies from 0.115 to 0.295.

- At all SAM P_{kill} levels, for both the active and the semi-active SSAD systems, the S-S-L firing policy provides higher $P_{noleakers}$ values than the S-L-S firing policy. The difference between $P_{noleakers}$ values provided by each firing policy varies from 0.093 to 0.278. for the semi-active SSAD system and from 0.018 to 0.105 for the active SSAD system.

- At all SAM P_{kill} levels the S-S-L firing policy kills threats at longer ranges than the S-L-S firing policy. For the semi-active SSAD system, the difference between average threat kill ranges with respect to firing policies varies from 0.5 NM to 0.87 NM. Whereas, for the active SSAD system, this difference varies from 0.395 NM to 0.745 NM.

- At all SAM P_{kill} levels, for both SSAD systems, the S-L-S firing policy expends about two fewer SAMs than the S-S-L firing policy.

In summary, for Scenario 1, the active SSAD system using the S-S-L firing policy provides better results for $P_{noleakers}$ and average threat kill range. This results from the inability of the semi-active SSAD system to simulataneously engage many threats. Thus, when there are more ASMs than illuminators, the semi-active SSAD system can be saturated. Whereas, the semi-active SSAD system using the S-S-L firing policy provides better results for average number of expended SAMs. Since in this analysis both SSAD systems are assumed to have 20 SAMs, the fewer expended SAM advantage is not as important as other MOEs. Therefore, for scenario 1, the active SSAD system using the S-S-L firing policy is better than the semi-active SSAD system using the S-S-L firing policy.

F. SCENARIO 2

In the second scenario the level of the stress is increased. Scenario 2 can be summarized as follows. Four ASMs approach a single ship with two raids. The first raid approaches the ship from the North, whereas the second raid approaches the ship from the East. Each raid has two ASMs. The first ASMs of each raid arrive the ship simultaneously. The second ASMs of each raid arrive the ship six seconds later. Each ASM in both raids flies at a cruise altitude of five meters. The starting distance of each ASM to the ship is 22.8 NM. Figure 11 illustrates a representative diagram of Scenario 2.

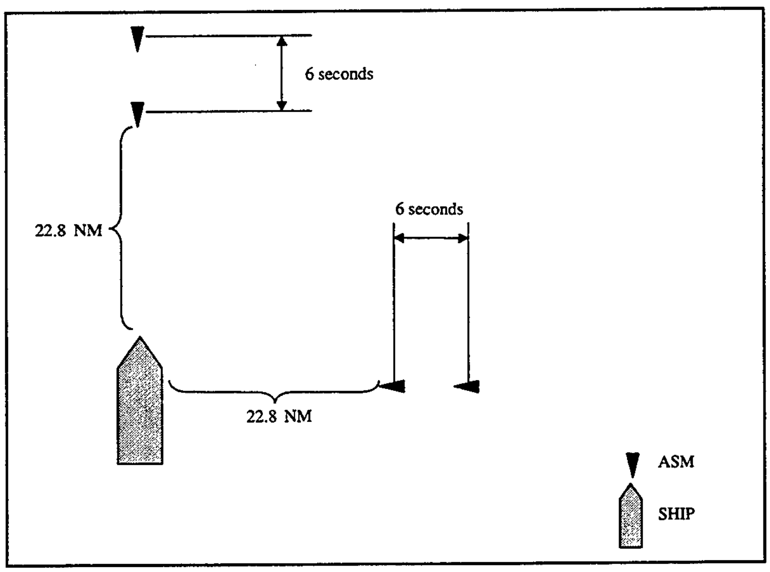


Figure 11. Representative Diagram of the Scenario 2.

G. COMPARATIVE ANALYSES FOR SCENARIO 2

In this analysis, both the active and the semi-active SSAD systems will be evaluated with a full SAM load out of 20 SAMs. Additionally, the semi-active SSAD system will be evaluated with two trackers having six-second tracker slew delays.

1. Comparative Analysis for the Primary MOE (Probability of No Leakers)

Figure 12 illustrates the probability of no leakers versus SAM P_{kill} values of the active and the semi-active SSAD systems as a function of firing policies for scenario 2.

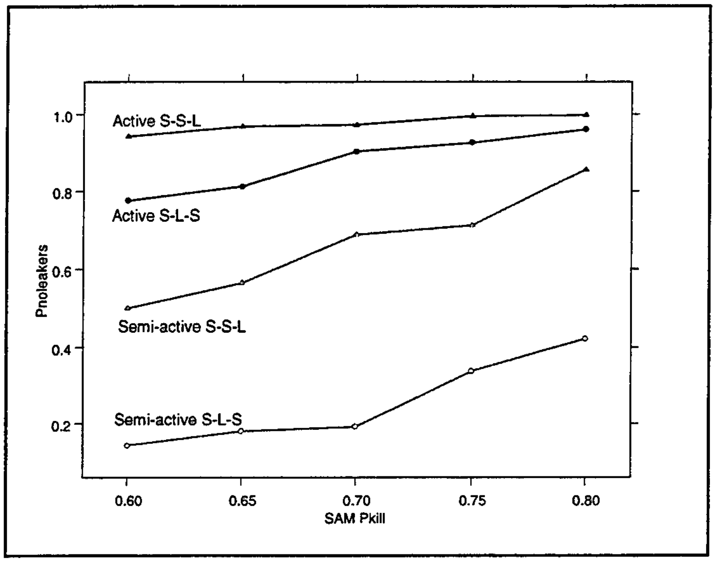


Figure 12. Probability of No Leakers ($P_{noleakers}$) versus SAM P_{kill} Values of the Active and the Semi-active SSAD Systems for Scenario 2.

Figure 12 shows that at all SAM P_{kill} levels the active SSAD system provides higher $P_{noleakers}$ values than the semi-active SSAD system. The difference between $P_{noleakers}$ values provided by the active and the semi-active S-S-L policies varies from 0.143 to 0.442. Whereas, the same distance for the active and the semi-active S-L-S policies varies from 0.538 to 0.71.

Additionally, at all SAM P_{kill} levels, for both the active and the semi-active SSAD systems, the S-S-L firing policy provides higher $P_{noleakers}$ values than the S-L-S firing policy. The difference between $P_{noleakers}$ values provided by each firing policy vary from 0.358 to 0.496. for the semi-active SSAD system and from 0.038 to 0.167 for the active SSAD system.

Figure 12 also shows that even at a 0.8 SAM P_{kill} level the semi-active S-L-S firing policy is not as effective as the semi-active S-S-L firing policy at a 0.6 SAM P_{kill}

level. This occurs because of a higher first salvo P_{kill} provided by the S-S-L firing policy. In stressing scenarios, missed salvos can be catastrophic. In fact, only the active SSAD system with a S-S-L firing policy provides adequate protection across the range of possible SAM P_{kill} values. (See Table E.7. and Table E.8. for detailed statistical analysis.)

2. Comparative Analysis for the Intermediate MOEs

a) Comparative Analysis for average number of expended SAMs

Figure 13 illustrates average number of expended SAMs versus SAM P_{kill} values of the active and the semi-active SSAD systems for scenario 2.

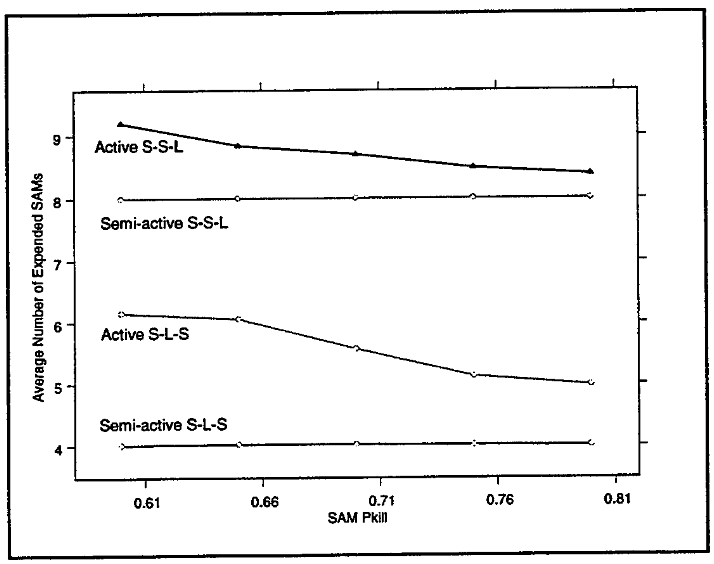


Figure 13. Average number of expended SAMs versus SAM Pkill values of the Active and the Semi-active SSAD System for Scenario 2.

Figure 13 shows that for both SSAD systems, at all SAM P_{kill} levels the S-S-L firing policy expends more SAMs than the S-L-S firing policy. For the semi-active SSAD system, the difference between average number of expended SAM values provided by each firing policy is approximately 4 at all SAM P_{kill} levels. Whereas, for the active SSAD system, this difference varies from 2.782 to 3.94.

The constant amount of expended SAMs of semi-active SSAD system firing policies indicates the effect of the tracker saturation and the tracker slew delay. This effect can be explained as follows: The ship has two ASMs coming from the North with a six-second delay in between. It also has two ASMs coming from the East with a six-second delay in between. There are two trackers with six-second slew delay aboard the ship. That is, it takes the tracker six-second to illuminate the second ASM after the first one has been destroyed.

Once a tracker illuminates the first missile from the North, the semi-active SSAD system using the S-S-L firing policy initially launches two SAMs. If these SAMs kill the first ASM, then the tracker has time to illuminate the second ASM and launch two more SAMs. If SAMs kill the second ASM, then the ship is saved from the attack coming from the North. A similar situation also goes for the attack from the East.

However, if the first two SAMs launched against the first ASM coming from the North miss their threat, then the ship launches two more SAMs against the first ASM. Even if the second launched SAMs kill the first ASM, the ship will be hit by the second ASM coming from the North, because the second ASM will approach too close to the ship and the tracker cannot illuminate the second ASM before the tracker slew delay is completed. After tracker slew delay passed, the ASM hits the ship and the simulation ends. This explanation shows that for the raid approaching from the North the semi-active S-S-L firing policy always expends four SAMs. Similarly for the raid approaching from the East the semi-active S-S-L firing policy also expends four SAMs. So, for two raids a total of eight SAMs are expended for Scenario 2. Thus, the maximum number of SAMs expended for the best and the worst case scenarios in the S-S-L firing policy are eight. This is indicated in the graph in the Figure 12.

A similar procedure holds for the S-L-S firing policy, except the S-L-S firing policy initially launches one SAM instead of two SAMs. So, the semi-active S-L-S firing policy expends two SAMs for the raid approaching from the North and also expends two SAMs for the raid approaching from the East. Therefore, the semi-active S-L-S firing policy expends a total of four SAMs for two raids. In other words, for the best and worst case scenarios for the S-L-S firing policy, the maximum number of ASMs expended by the semi-active SSAD system is four. This is indicated in the graph in the Figure 12 also. (See Table E.9. and Table E.10. for detailed statistical analysis.)

b) Comparative Analysis for average kill range of threats

Figure 14 illustrates the average threat kill range versus SAM P_{kill} values of the active and the semi-active SSAD systems for scenario 2.

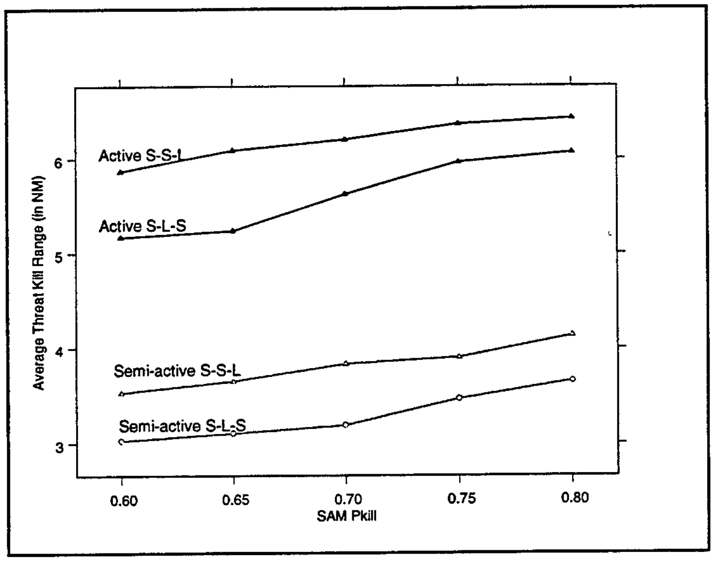


Figure 14. Average threat kill range versus SAM Pkill values of the Active and the Semi-active SSAD systems for Scenario 2.

Figure 14 shows that for both SSAD systems, at all SAM P_{kill} levels, the S-S-L firing policy kills threats at a longer range than the S-L-S firing policy. For the semi-active SSAD system, the difference between average threat kill ranges with respect to firing policies varies from 0.436 NM to 0.643 NM. Whereas, for the active SSAD system, this difference varies from 0.5 NM to 0.87 NM. (See Table E.11. and Table E.12. for detailed statistical analysis)

3. Summary of the comparative analyses of MOEs for Scenario 2

Recall that in scenario 2, the ship, with a 20 SAMs load out, tries to defend itself against two approaching ASMs from the North and two approaching ASMs from the East with a six-second time interval between each other. In conjunction with conditions given above, SSAD-Sim simulation results and comparative analysis results can be summarized as follows.

- The active SSAD system provides significantly higher $P_{noleakers}$ values than the semi-active SSAD system. The difference between $P_{noleakers}$ values provided by active and the semi-active S-S-L policies varies from 0.143 to 0.442. Whereas, the same distance for the active and the semi-active S-L-S policies varies from 0.538 to 0.71.

- At all SAM P_{kill} levels, for both the active and the semi-active SSAD systems, the S-S-L firing policy provides significantly higher $P_{noleakers}$ values than the S-L-S firing policy. The difference between $P_{noleakers}$ values provided by each firing policy varies from 0.358 to 0.496 for the semi-active SSAD system and from 0.038 to 0.167 for the active SSAD system.

- At all SAM P_{kill} levels the S-S-L firing policy kills threats at longer ranges than the S-L-S firing policy. For the semi-active SSAD system, the difference between average threat kill ranges with respect to firing policies varies from 0.436 NM to 0.643 NM. Whereas, for the active SSAD system, this difference varies from 0.5 NM to 0.87 NM.

- At all SAM P_{kill} levels the S-S-L firing policy expends more SAMs than the S-L-S firing policy. For the semi-active SSAD system the S-S-L firing policy expends approximately 4 more SAMs than the S-L-S firing policy. Whereas, for the active SSAD system, the S-S-L firing policy expends more SAMs variying from 2.782 to 3.94 than the S-L-S firing policy.

In summary, for Scenario 2, the active SSAD system using the S-S-L firing policy provides better results for $P_{noleakers}$ and average threat kill range. Whereas, the semi-active SSAD system using the S-S-L firing policy provides better results for average number of expended SAMs. Since in this analysis both SSAD systems are assumed to have 20 SAMs, the fewer expended SAM advantage is not as important as other MOEs.

Therefore, for scenario 2, the active SSAD system using the S-S-L firing policy is better than the semi-active SSAD system using the S-S-L firing policy.

V. SENSITIVITY ANALYSIS

Thus far, SSAD-Sim simulation results have been used in the comparative analysis. By analyzing SSAD-Sim simulation results it has been shown that:

- Among the alternatives, how the better firing policy can be determined.
- Among the two competitive systems, how the better Ship Self Air Defense (SSAD) system can be determined.

Analysis applications of SSAD-Sim are not limited to those given above. SSAD-Sim can also be used efficiently for sensitivity analysis of key parameters. By doing sensitivity analysis, this chapter shows the robustness of the previous findings to variables that are important to ship self air defense. In the remainder of this chapter, sensitivity analysis applications of SSAD-Sim simulation results will be shown. For the sensitivity analysis of the tracker number and the tracker slew delay, scenario 2 using the semi-active SSAD system with the Shoot-Shoot-Look (S-S-L) firing policy is evaluated. Whereas, for the sensitivity analysis of the Surface-to-Air Missile (SAM) number, scenario 1 using the active SSAD system with the S-S-L firing policy is evaluated.

Recall that in scenario 2, the ship, with a 20 SAMs load out, tries to defend itself against two approaching ASMs from the North and two approaching ASMs from the East, with a six-second time interval between each other. In scenario 2, the semi-active SSAD system provides low $P_{noleakers}$ values. Even with the best firing policy, (i.e., the S-S-L firing policy) $P_{noleakers}$ values provided by the semi-active SSAD system are within the range of 0.5 to 0.855. (For all $P_{noleakers}$ values with respect to SAM P_{kill} values, see Table E.1.) The main reason for low $P_{noleakers}$ values is tracker saturation. Mainly, two factors affect tracker saturation: the number of trackers and the tracker slew delay. This chapter continues with the sensitivity analyses of these factors.

A. TRACKER NUMBER SENSITIVITY

The tracker number sensitivity of scenario 2 is investigated by using the semi-active SSAD system with its best firing policy for scenario 2 (i.e., the S-S-L firing policy). In this analysis, the semi-active SSAD system is assumed to have 20 SAMs and six-second tracker slew delay. The number of the trackers in the semi-active SSAD system will be varied from two to four. (Note that the most frigates in the world navies have two trackers.) So, it is expected that a greater number of trackers will decrease tracker saturation. Hence, higher $P_{noleakers}$ will be obtained.

Figure 15 illustrates sensitivity analysis of tracker numbers of the semi-active SSAD system using the S-S-L firing policy for scenario 2.

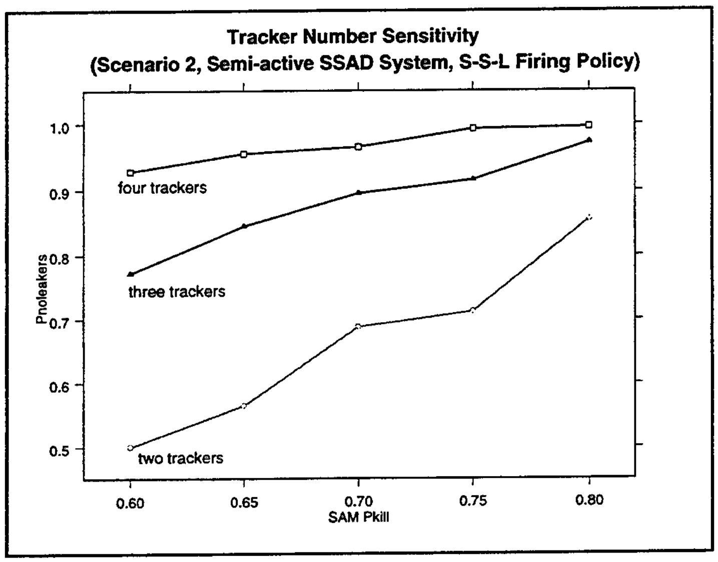


Figure 15. $P_{noleakers}$ versus SAM P_{kill} values with two, three, and four trackers.

Figure 15 shows that as number of trackers increases $P_{noleakers}$ values increase. Increasing number of trackers from two to three increases the $P_{noleakers}$ values in the range of 0.117 to 0.272. Increasing number of trackers from three to four increases the $P_{noleakers}$ values in the range of 0.023 to 0.156.

Additionally, Figure 15 shows that as SAM P_{kill} values increase, the difference between $P_{noleakers}$ values provided by different trackers decreases. Especially, the difference between three-tracker and four-tracker semi-active SSAD systems is very small at high SAM P_{kill} values. For example, at 0.8 SAM P_{kill} level difference between $P_{noleakers}$ values provided by three-tracker and four-tracker semi-active SSAD systems is 0.023.

On the other hand, the biggest differences between $P_{noleakers}$ values occur at 0.60 SAM P_{kill} value.

However, increasing the SAM P_{kill} value by 0.2 is more effective than adding a tracker.

B. TRACKER SLEW DELAY SENSITIVITY

The tracker slew delay sensitivity of scenario 2 is investigated using the semi-active SSAD system with the S-S-L firing policy. In this analysis, the semi-active SSAD system is assumed to have 20 SAMs and two trackers. The following values have been used as the tracker slew delay: six seconds, three seconds and zero second (no delay). It is expected that less tracker slew delay will decrease tracker saturation. Hence, higher $P_{noleakers}$ will be obtained.

Figure 16 illustrates sensitivity analysis of tracker slew delay of the semi-active SSAD system using the S-S-L firing policy for scenario 2.

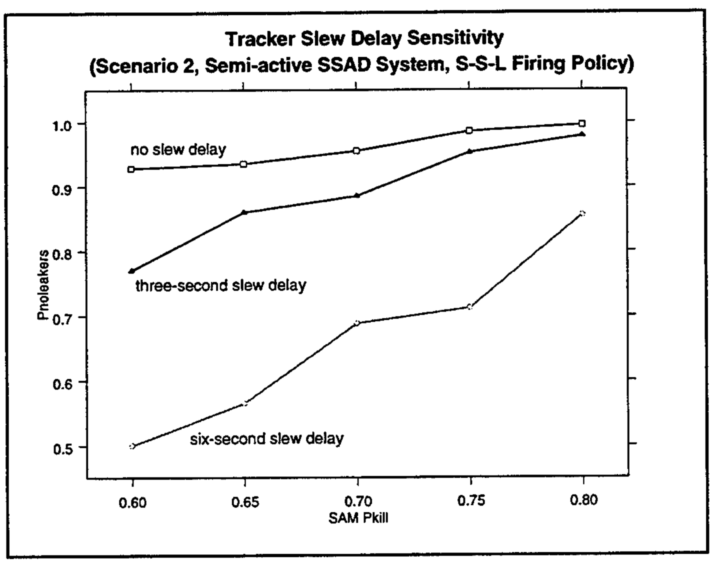


Figure 16. $P_{noleakers}$ versus SAM P_{kill} values with six, three and zero seconds tracker slew delays.

As seen on Figure 16, as tracker slew delay decreases $P_{noleakers}$ values increase. Decreasing tracker slew delay from six-second to three-second increases the $P_{noleakers}$

values in the range of 0.123 to 0.27. Decreasing tracker slew delay from three-second to zero-second increases the $P_{noleakers}$ values in the range of 0.017 to 0.158.

Additionally, Figure 16 shows that as SAM P_{kill} values increase the difference between $P_{noleakers}$ values provided by different tracker-slew delays decreases. Especially, the difference between three-second and zero-second tracker slew delays is very small at high SAM P_{kill} values. For example, at 0.8 SAM P_{kill} level difference between $P_{noleakers}$ values provided by three-second and zero-second tracker slew delay semi-active SSAD systems is 0.017. On the other hand, the biggest differences between $P_{noleakers}$ values occur at 0.60 SAM P_{kill} value.

C. SAM NUMBER SENSITIVITY

Heretofore, in all cases, the S-S-L firing policy provided better protection than the S-L-S firing policy. Now, the following question is addressed: When does the S-L-S firing policy provide better protection than the S-S-L firing policy?

The major parameter affecting the protection quality of firing policies is the number of SAMs in the inventory. Effects of the number of SAMs can be explained with the following example. Three ASMs approach the ship and there are four SAMs in the inventory. In order to protect the ship, a myopic S-S-L firing policy initially assigns two SAMs to the first ASM. Then, the S-S-L firing policy also assigns the remaining two SAMs to the second ASM. However, since the S-S-L firing policy assigned all SAMs of its inventory to the first two ASMs, it cannot assign any SAM to the third ASM. Hence, no matter how successfully the first two ASMs are defeated, the third ASM does not encounter any counter attack and it hits the ship. On the other hand, for the same example, the S-L-S firing policy initially assigns one SAM to each ASM and one SAM remains in the inventory. So, if one of the SAMs fail to kill one of the approaching ASMs, the S-L-S firing policy has a chance to use its remaining SAM against this ASM. In this example, since the S-L-S firing policy assigns one SAM to each approaching ASM, it provides higher $P_{noleakers}$ values than the S-S-L firing policy.

In order to show which firing policy provides the better protection for the ship depending on the SAM inventory, SSAD-Sim simulation results can be used efficiently. An example study is conducted for scenario 1 for the active SSAD system as follows.

Recall that in scenario 1, the ship tries to defend itself against three approaching ASMs with a six-second time interval between each other. In order to see the effectiveness of the number of SAMs in the inventory, the first SSAD-Sim simulation run is conducted with five SAMs. Then, the number of SAMs is increased by one and SSAD-Sim simulation runs are repeated. This process continues until the number of SAMs reaches to eight.

Figure 17 illustrates sensitivity analysis of SAM number of the active SSAD system using the S-S-L and the S-L-S firing policies for scenario 1.

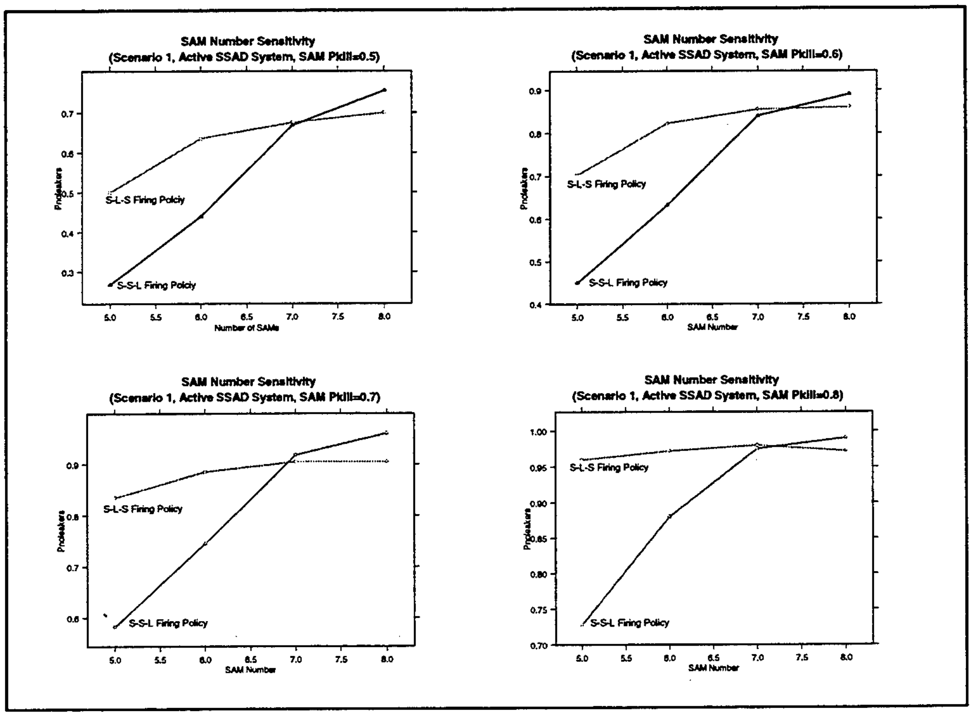


Figure 17. $P_{noleakers}$ versus SAM number values for 0.5, 0.6, 0.7, and 0.8 SAM P_{kill} values.

Figure 17 shows that when the number of SAMs in the inventory is less than seven the S-L-S firing policy provides higher $P_{noleakers}$ values than the S-S-L firing policy.

When there are five SAMs in the inventory the S-L-S firing policy provides higher $P_{noleakers}$ values varying from 0.232 to 0.253 than the S-S-L firing policy. When there are six SAMs in the inventory the S-L-S firing policy provides higher $P_{noleakers}$ values varying from 0.092 to 0.195 than the S-S-L firing policy. When there are seven SAMs in the inventory the difference between $P_{noleakers}$ values provided by the S-L-S and the S-S-L firing policies are not significant. However, since the S-L-S firing policy expends fewer SAMs, it is preferred. With seven SAMs in the inventory the S-L-S firing policy provides higher $P_{noleakers}$ values varying from 0.007 to 0.015. Whereas, at the 0.7 SAM P_{kill} level the S-S-L firing policy provides 0.013 higher $P_{noleakers}$ value than the S-L-S firing policy. On the other hand, after the inventory level reaches eight the S-S-L firing policy provides higher $P_{noleakers}$ values than the S-L-S firing policy. With eight SAMs in the inventory the S-S-L firing policy provides higher $P_{noleakers}$ values varying from 0.01 to 0.055.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. Conclusions of SSAD-Sim

In order to simulate a Ship Self Air Defense (SSAD) system, this thesis has developed a prototype discrete event SSAD simulation model called SSAD-Sim. SSAD-Sim is a platform independent, object-oriented, modular and expandable simulation tool. Analytical applications made in this thesis showed that:

- SSAD-Sim has enough capability to handle a large number of simulation runs. (In this thesis, over 25,000 SSAD-Sim simulation runs were conducted to explore various features of SSAD systems)
- SSAD-Sim can be efficiently used to assist in determining the better SSAD system among the alternative SSAD systems.
- SSAD-Sim can be efficiently used to assist in determining the better firing policy among the alternative firing policies.
- SSAD-Sim can be efficiently used for sensitivity analysis of key parameters of SSAD systems such as tracker number, tracker slew delay, and Surface-to-Air Missile (SAM) number.

In addition, SSAD-Sim can be used to provide useful insight for the following objectives:

- To assist decision authorities to select the best SSAD system.
- To assess suitable tactics for different threat environments.
- To determine the necessary modifications to SSAD systems, in conjunction with developments in threat characteristics.
- To provide a training opportunity for the users of SSAD systems.

Furthermore, the component-based modular nature of SSAD-Sim provides the following advantages to improve SSAD-Sim for further studies:

- SSAD-Sim components can be used in multiple applications without any change.
- With a slight modification, the functionality and the task of SSAD-Sim components can be changed significantly.
- SSAD-Sim components can be connected to each other easily.

2. Conclusions of Comparative Analyses

Chapter IV presents typical analytical calculations that can be obtained from the SSAD-Sim. During the analytical calculations, hypothetical effective analysis of two SSAD systems, the active and the semi-active SSAD systems, were made. Both SSAD systems used Shoot-Look-Shoot (S-L-S) and Shoot-Shoot-Look (S-S-L) firing policies with a 20 SAM load out.

Comparative analyses showed that for all threat environments, with the assumed system effectiveness, the active SSAD system, using the S-S-L firing policy provides the most effective results. (See Chapter IV for the detailed comparative analyses)

3. Conclusions of Sensitivity Analyses

Chapter V presents the sensitivity analysis applications of key parameters of the SSAD systems. By using SSAD-Sim simulation, the following conclusions were made from the sensitivity analysis.

- As the number of trackers increases $P_{noleakers}$ values increase. However, the increment level of $P_{noleakers}$ values decreases as SAM P_{kill} values increase.
- As tracker slew delay decreases $P_{noleakers}$ values increase. However, the increment level of $P_{noleakers}$ values decreases as SAM P_{kill} values increase.
- In low SAM inventory levels, the S-L-S firing policy provides higher $P_{noleakers}$ values than the S-S-L firing policy.

B. RECOMMENDATIONS FOR FURTHER STUDIES ON SSAD-Sim

Since a SSAD system consists of complicated processes and elements, modeling of all its features is a very complex and time consuming process. One of the best ways to model a SSAD system is to develop a main structure first and then detail this main structure with further additions and modifications. SSAD-Sim was developed as the main structure to model a SSAD system. In the development of SSAD-Sim, only the main aspects of the SSAD system are considered and second order properties are omitted. Omitted aspects are discussed with the assumptions given in Chapter III. As the level of detail of SSAD-Sim increases the omitted aspects can be modeled easily by using the component-based modular nature of SSAD-Sim. The following modifications and additions can be done as further study:

- By adding a new component, soft kill counter measure systems (decoys, chaff, and radar jamming devices) can be modeled. So, effectiveness of soft kill and hard kill counter measures can be compared by using SSAD-Sim simulation results.

- By adding a new component or modifiying the BasicSensor component, a continuous looking sensor can be modeled as the surveillance system. So, effectiveness of a scanning search radar and continuous looking radar can be compared by using the SSAD-Sim.

- By modifiying OutgoingMissile component, SAMs can be modeled to produce nonlinear movement, so the accuracy of SAM movements are increased.

- By modifiying TargetMover component, threats can be modeled to produce nonlinear movement, so the accuracy of threat movements are increased.

APPENDIX A: GOODNESS OF FIT OF RANDOM NUMBERS

Since the SSAD-Sim is a Monte Carlo simulation, it depends on the quality of the random numbers it uses. The SSAD-Sim needs two kinds of random numbers: uniformly distributed and normally distributed. Each type of random number is obtained from the random number generator of the Simkit package. It produces the same stream of random numbers produced by the random number generator in Simscript II, a general purpose simulation language. Simkit has 10 random streams and for each stream a desired seed number can be entered. The period of the Simkit random number generator is approximately 2^{31}.

The purpose of this appendix is to explore the goodness of the random numbers used in SSAD-Sim runs. To do this, first, random numbers are drawn and put into an output file. Second, the goodness of the random numbers is analyzed by using statistical techniques.

A. OBTAINING THE RANDOM NUMBERS

In order to obtain random numbers, the RandomNumberTester class is added to the SSAD-Sim. The main function of this class is to draw desired quantity of random numbers from the Simkit and put them into a selected output file.

B. GOODNESS OF FIT TEST FOR UNIFORM RANDOM NUMBERS

In this section, the data are 2000 uniform random numbers drawn from the Simkit in the [0,1] interval. The following parts of this section analyze the goodness of fit of the data generated.

1. Summary Statistics for the data

Minimum Observation:	0.001
First Quartile of Observations:	0.253
Mean of Observations:	0.497
Median of Observations:	0.487
Third Quartile of Observations:	0.746
Maximum Observation:	0.998
Total Number of Observations:	2000.000
Variance of Observations:	0.082
Standard Deviation of Observation	0.286

The summary statistics values, given above, are very close results to the theoretical calculations.

2. The Histogram and the Quartile Plots of the data

Figure A.1 illustrates the histogram of the data.

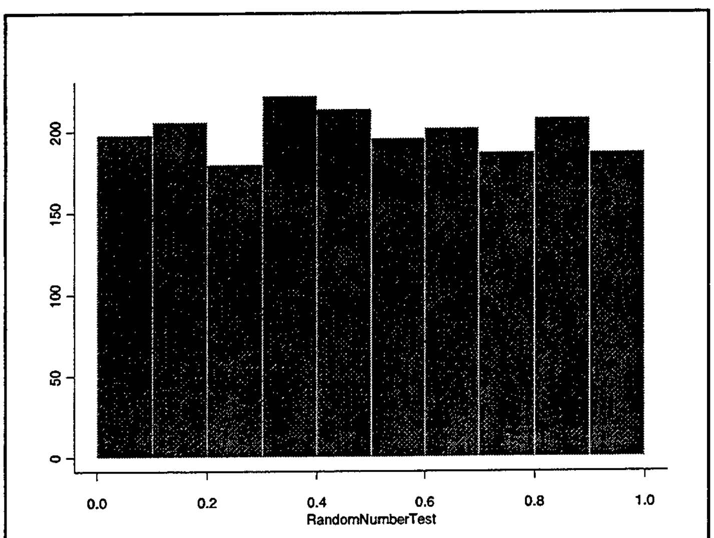


Figure A.1. Histogram of 2000 Uniform Random Numbers Drawn from the Simkit in the [0,1] Interval.

Figure A.2 illustrates the quartile plot of the data:

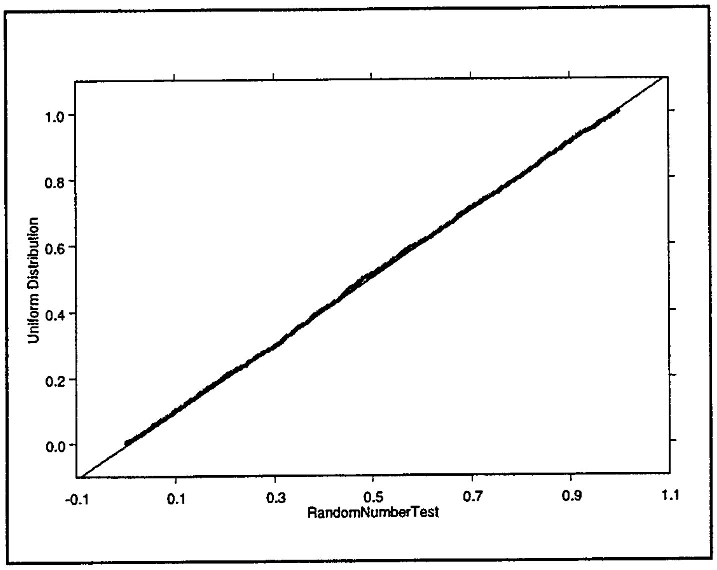


Figure A.2. Quartile Plot of 2000 Uniform Random Numbers Drawn from the Simkit in the [0,1] Interval.

Both the histogram and the quartile plots show that the data fits the uniform distribution in the [0,1] interval.

3. Kolmogorov-Smirnov Goodness of Fit Test

a) Hypotheses

H_O = The data is uniformly distributed in the [0,1] interval

H_A = Data is not uniformly distributed in the [0,1] interval.

b) Confidence Level

95% Confidence level is used. Hence, α is equal to 0.05.

c) Test Statistics

If p-value is less than or equal to α reject H_O at level α Else, do not reject H_O at level α

d) Kolmogorov-Smirnov goodness of Fit Test Results

Calculated Kolmogorov-Smirnov value = 0.0157

p-value = 0.706

e) Decision

Results from the Kolmogorov-smirnov goodness of fit test show that p-value is greater than α. So, H_O cannot be rejected at 95% confidence level. Hence, the data fits a uniform distributed in the [0,1] interval.

C. GOODNESS OF FIT TEST FOR NORMAL RANDOM NUMBERS

In this section, the data are 2000 normal random numbers drawn from the Simkit with mean equal to 0 and the standard deviation equal to 1. The following parts of this section analyze the goodness of the data.

1. Summary Statistics for the data

Minimum Observation:	-3.475
First Quartile of Observations:	-0.710
Mean of Observations:	-0.018
Median of Observations:	-0.040
Third Quartile of Observations:	0.658
Maximum Observation:	3.543
Total Number of Observations:	2000.000
Variance of Observations:	1.050
Standard Deviation of Observations:	1.025

The summary statistics values, given above, are very close to the theoretical calculations.

2. The Histogram and the Quartile Plots of the data

Figure A.3. illustrates the histogram of the data.

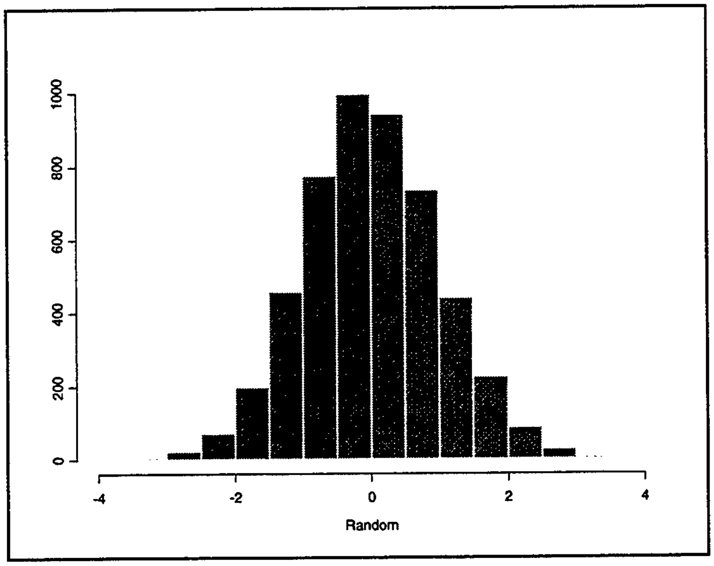


Figure A.3. Histogram of 2000 Normal Random Numbers Drawn from the Simkit with Mean Equal to 0 and the Standard Deviation Equal to 1.

Figure A.4. illustrates the quartile plot of the data:

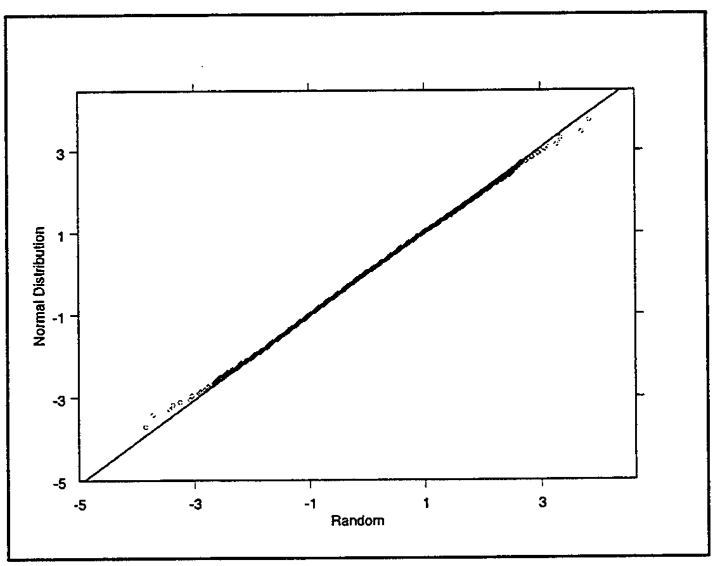


Figure A.4. Quartile plot of of 2000 Normal Random Numbers Drawn from the Simkit with Mean Equal to 0 and the Standard Deviation Equal to 1.

On the plots above, neither positive nor negative skew is seen. But especially in the quartile plot lighter tails than the standard normal distribution are seen.

3. Kolmogorov-Smirnov Goodness of Fit Test

a) Hypotheses

H_O = The data is normally distributed with mean equal to 0 and the standard deviation equal to 1.

H_A = The data is not normally distributed with the parameters given in the null hypothesis.

b) Confidence Level

95% Confidence level is used. Hence, α is equal to 0.05.

c) Test Statistics

If p-value is less than or equal to α reject H_O at level α Else, do not reject H_O at level α

d) Kolmogorov-Smirnov goodness of Fit Test Results

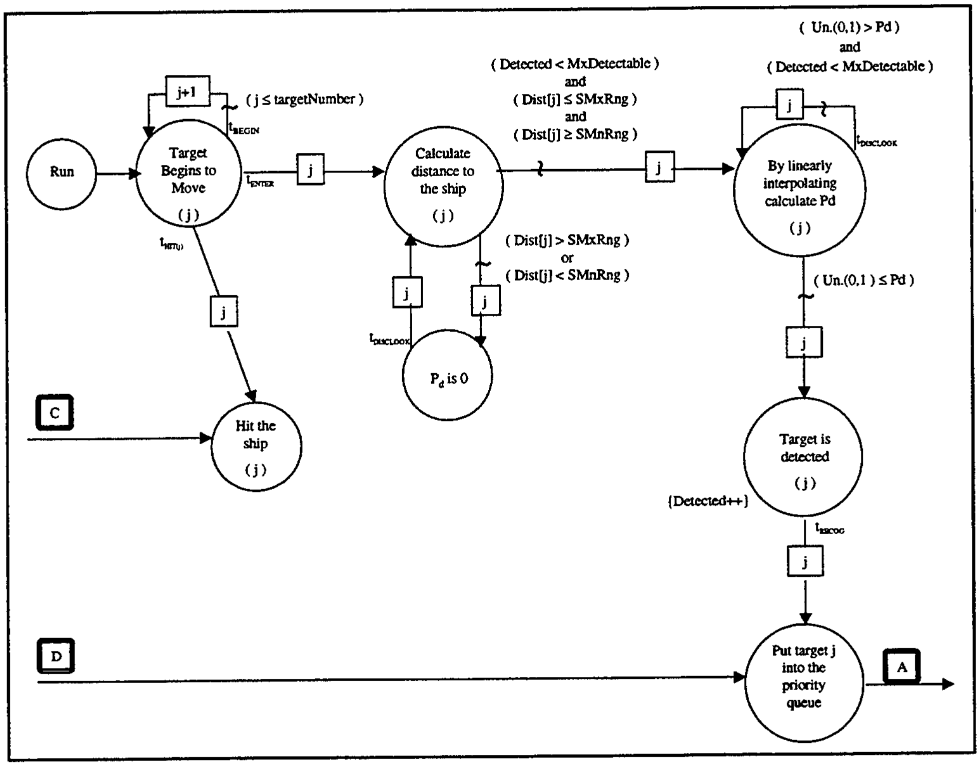
Calculated Kolmogorov-Smirnov value = 0.0265

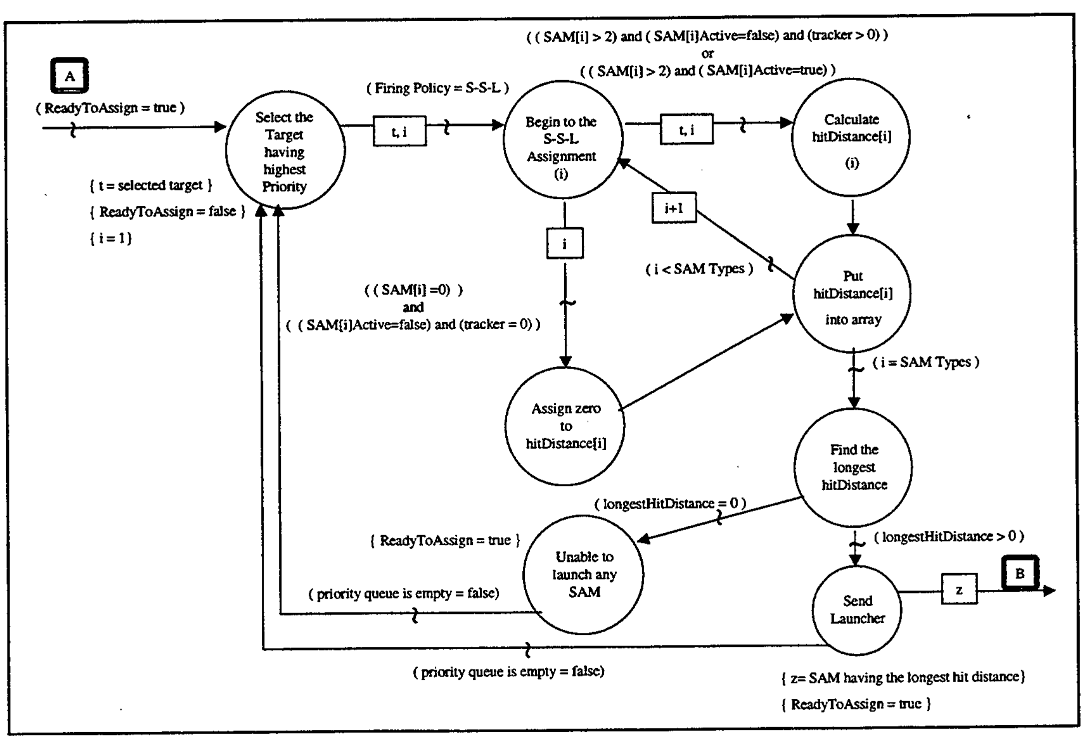
p-value = 0.1193

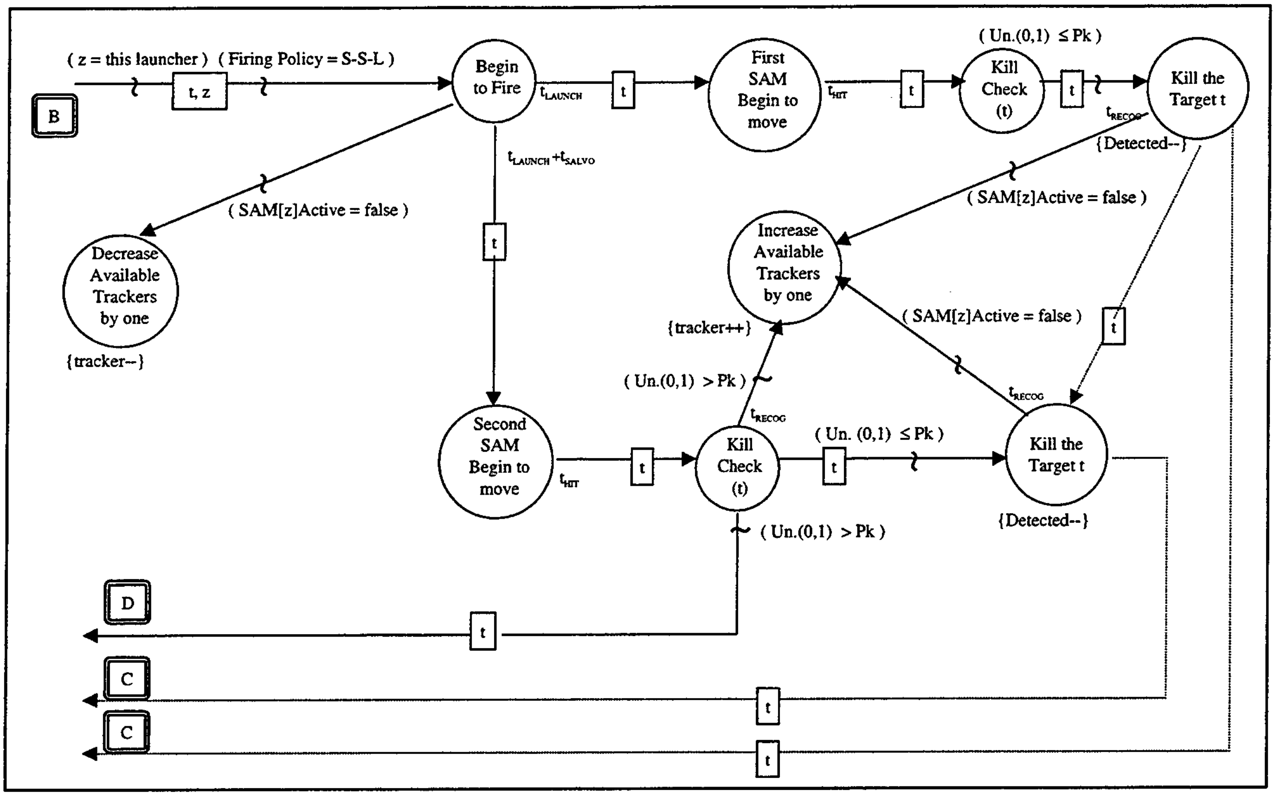
e) Decision

Results from the Kolmogorov-smirnov goodness of fit test show that p-value is greater than α. So, H_O cannot be rejected at 95% confidence level. Hence, the data fits normally distributed with mean equal to zero and standard deviation equal to one.

APPENDIX B: EVENT GRAPH OF SHIP SELF AIR DEFENSE SIMULATION







Indices Used in the Event Graph:

j = Threat indices.

t = Threat having the highest priority.

i = SAM indices.

z = Assigned SAM indices.

Variables Used in the Event Graph:

targetNumber = Total number of targets.

Detected = Current detected target numbers.

MxDetectable = Maximum number of targets can be detected by the Sensor.

SMxRng = Sensor Maximum Range.

SMnRng = Sensor Minimum Range.

Pd = Probability of detection of the sensor.

Dist[j] = Current distance between the ship and the j_{th} target.

ReadyToAssign = Boolean variable showing the ability to SAM assign of the fire control system.

FiringPolicy = Current firing policy of the fire control system.

SAM[i] = Total number of SAMs in the i_{th} launcher.

SAM[i]Active = Guide status of SAMs in the i_{th} launcher. (If SAMs in the i_{th} launcher is active, then true. Otherwise false.)

tracker = Current available number of trackers.

hitDistance[i] = Calculated hit distance of SAM in the i_{th} launcher.

longestHitDistance = Maximum of all calculated hitDistance[i]s.

Pk = Probability of killing of the SAM to the threat.

t_{BEGIN} = Threats' beginning time to move.

$t_{HIT(j)}$ = Hit time of the j_{th} threat to the ship.

t_{ENTER} = Threats' entering time to the sensor maximum range.

$t_{DISCLOOK}$ = Discrete looking time of the sensor.

t_{RECOG} = Recognition delay.

t_{LAUNCH} = Launch delay.

t_{SALVO} = Salvo delay.

t_{HIT} = Hit time of the SAM to the threat.

APPENDIX C: REPRESENTATIVE OUTPUT FILE OF SSAD-SIM SIMULATION

Scenario1 three ASMs approaching from the North
The Active SSAD System is used with S-L-S Firing Policy.
There are 7 Active SAMs in the inventory. SAM Pkill is 0.60

Iteration	AverageKil l Range.	Maximum Kill Range.	Minimum Kill Range.	Number of Killed Targets	Number of Leakers	Number of Expended Missiles
0	5.821	6.960	3.769	3.000	0.000	4.000
1	6.737	6.909	6.647	3.000	0.000	3.000
2	6.810	6.983	6.475	3.000	0.000	3.000
3	5.758	6.901	3.708	3.000	0.000	4.000
4	5.687	6.799	3.474	3.000	0.000	4.000
5	6.836	7.019	6.578	3.000	0.000	3.000
6	4.862	6.770	1.269	3.000	0.000	5.000
7	3.453	6.805	0.000	2.000	1.000	6.000
8	6.840	6.967	6.655	3.000	0.000	3.000
9	4.575	7.137	0.000	2.000	1.000	5.000
10	3.906	6.997	1.060	3.000	0.000	6.000
11	6.736	6.843	6.617	3.000	0.000	3.000
12	5.828	7.075	3.374	3.000	0.000	4.000
13	6.846	6.958	6.642	3.000	0.000	3.000
14	6.749	6.809	6.683	3.000	0.000	3.000
15	7.060	7.117	6.997	3.000	0.000	3.000
16	6.815	6.964	6.607	3.000	0.000	3.000
17	3.392	6.545	0.000	2.000	1.000	6.000
18	6.820	6.963	6.541	3.000	0.000	3.000
19	4.779	6.757	3.717	3.000	0.000	5.000

Summary report

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range.	MaximumT hreat Kill Range.	Minimum Threat Kill Range.	Average Number of Killed Threats	Average Number of ExpendedSA Ms	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.600	0.850	5.816	6.914	4.341	2.850	3.950	0.150	20.000	17.000

APPENDIX D: SUMMARY SIMULATION RESULTS

A. SCENARIO 1 SUMMARY SSAD-SIM SIMULATION RESULTS

Semi-active SSAD System using S-L-S Firing Policy

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.600	0.550	3.508	5.365	1.348	2.352	3.908	0.648	400	220
0.650	0.680	3.831	5.657	1.700	2.575	3.818	0.425	400	272
0.700	0.700	3.952	5.732	1.845	2.600	3.775	0.400	400	280
0.750	0.782	4.166	5.802	2.093	2.728	3.682	0.272	400	313
0.800	0.865	4.450	5.911	2.506	2.832	3.528	0.168	400	346

Semi-active SSAD System using S-S-L Firing Policy

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimu mThreat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.600	0.828	4.378	5.859	2.478	2.808	6.532	0.192	400	331
0.650	0.842	4.493	5.911	2.610	2.822	6.442	0.178	400	337
0.700	0.878	4.662	5.968	2.828	2.868	6.312	0.132	400	351
0.750	0.890	4.849	6.063	3.036	2.888	6.188	0.112	400	356
0.800	0.958	4.953	6.078	3.274	2.958	6.155	0.042	400	383

Active SSAD System using S-L-S Firing Policy

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.600	0.845	5.130	6.684	3.165	2.825	4.642	0.175	400	338
0.650	0.898	5.511	6.821	3.724	2.895	4.275	0.105	400	359
0.700	0.900	5.625	6.886	3.937	2.895	4.162	0.105	400	360
0.750	0.950	5.893	6.871	4.523	2.950	3.905	0.050	400	380
0.800	0.98	6.076	6.919	4.919	2.980	3.730	0.020	400	392

Active SSAD System using S-S-L Firing Policy

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	AverageN umber of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.600	0.950	5.873	6.82	4.542	2.945	6.868	0.055	400	380
0.650	0.968	6.000	6.852	4.796	2.935	6.682	0.065	400	378
0.700	0.970	6.168	6.877	5.158	2.970	6.575	0.030	400	388
0.750	0.990	6.354	6.929	5.523	2.990	6.360	0.010	400	396
0.800	0.998	6.471	6.934	5.820	2.998	6.225	0.002	400	399

B. SCENARIO 2 SUMMARY SSAD-SIM SIMULATION RESULTS

Semi-active SSAD System using S-L-S Firing Policy

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	AverageN umber of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.600	0.142	3.028	5.417	0.407	2.442	4.012	1.558	400	57
0.650	0.180	3.105	5.461	0.491	2.578	4.022	1.422	400	72
0.700	0.192	3.189	5.655	0.525	2.748	4.022	1.252	400	77
0.750	0.338	3.463	5.764	0.944	2.992	4.012	1.008	400	135
0.800	0.422	3.653	5.898	1.205	3.212	4.008	0.788	400	169

Semi-active SSAD System using S-S-L Firing Policy

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.600	0.500	3.529	5.875	1.163	3.368	8.000	0.632	400	200
0.650	0.565	3.650	5.919	1.325	3.475	8.000	0.525	400	226
0.700	0.688	3.832	6.009	1.683	3.638	8.000	0.362	400	275
0.750	0.712	3.899	6.042	1.725	3.698	8.000	0.302	400	285
0.800	0.855	4.129	6.056	2.170	3.850	8.000	0.150	400	342

Active SSAD System using S-L-S Firing Policy

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.600	0.775	5.174	6.880	2.616	3.74	6.155	0.260	400	310
0.650	0.812	5.241	6.868	2.720	3.795	6.058	0.205	400	325
0.700	0.902	5.625	6.911	3.514	3.890	5.570	0.110	400	361
0.750	0.925	5.964	6.977	4.109	3.922	5.120	0.078	400	370
0.800	0.960	6.066	6.968	4.376	3.960	4.982	0.040	400	384

Active SSAD System using S-S-L Firing Policy

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.600	0.942	5.871	6.911	4.147	3.938	9.195	0.062	400	377
0.650	0.968	6.092	6.937	4.626	3.968	8.840	0.032	400	387
0.700	0.972	6.206	6.957	4.888	3.970	8.695	0.030	400	389
0.750	0.995	6.366	6.968	5.275	3.995	8.485	0.005	400	398
0.800	0.998	6.425	6.975	5.452	3.998	8.380	0.002	400	399

C. SCENARIO 2 TRACKER NUMBER SENSITIVITY SSAD-SIM SIMULATION RESULTS

Semi-active SSAD System using S-S-L Firing Policy with Two Trackers

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.600	0.500	3.529	5.875	1.163	3.368	8.000	0.632	400	200
0.650	0.565	3.650	5.919	1.325	3.475	8.000	0.525	400	226
0.700	0.688	3.832	6.009	1.683	3.638	8.000	0.362	400	275
0.750	0.712	3.899	6.042	1.725	3.698	8.000	0.302	400	285
0.800	0.855	4.129	6.056	2.170	3.850	8.000	0.150	400	342

Active SSAD System using S-S-L Firing Policy with Three Trackers

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.600	0.772	4.420	6.117	1.712	3.758	8.910	0.242	400	309
0.650	0.845	4.524	6.106	1.955	3.838	8.805	0.162	400	338
0.700	0.895	4.795	6.147	2.257	3.895	8.445	0.105	400	358
0.750	0.915	4.815	6.153	2.304	3.915	8.460	0.085	400	366
0.800	0.972	5.024	6.169	2.655	3.972	8.220	0.028	400	389

Active SSAD System using S-S-L Firing Policy with Four Trackers

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range.	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.600	0.928	5.077	6.127	3.231	3.918	9.285	0.082	400	371
0.650	0.955	5.221	6.158	3.523	3.955	9.090	0.045	400	382
0.700	0.965	5.437	6.159	4.107	3.962	8.700	0.038	400	386
0.750	0.992	5.677	6.189	4.766	3.992	8.345	0.008	400	397
0.800	0.995	5.723	6.193	4.869	3.995	8.315	0.005	400	398

D. SCENARIO 2 TRACKER SLEW DELAY SENSITIVITY SSAD-SIM SIMULATION RESULTS

Semi-active SSAD System using S-S-L Firing Policy with Six-Second Tracker Slew Delay

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.600	0.500	3.529	5.875	1.163	3.368	8.000	0.632	400	200
0.650	0.565	3.650	5.919	1.325	3.475	8.000	0.525	400	226
0.700	0.688	3.832	6.009	1.683	3.638	8.000	0.362	400	275
0.750	0.712	3.899	6.042	1.725	3.698	8.000	0.302	400	285
0.800	0.855	4.129	6.056	2.170	3.850	8.000	0.150	400	342

Active SSAD System using S-S-L Firing Policy with Three-Second Tracker Slew Delay

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.600	0.770	4.229	6.406	1.870	3.708	8.910	0.292	400	308
0.650	0.860	4.442	6.484	2.203	3.830	8.755	0.170	400	344
0.700	0.885	4.534	6.545	2.478	3.865	8.638	0.135	400	354
0.750	0.952	4.841	6.626	2.900	3.948	8.390	0.052	400	381
0.800	0.978	4.915	6.633	3.133	3.975	8.300	0.025	400	391

Active SSAD System using S-S-L Firing Policy with No Tracker Slew Delay

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.600	0.928	4.875	6.729	2.893	3.920	9.090	0.080	400	371
0.650	0.935	4.961	6.716	3.010	3.928	9.000	0.072	400	374
0.700	0.955	5.190	6.812	3.393	3.955	8.685	0.045	400	382
0.750	0.985	5.314	6.831	3.699	3.985	8.510	0.015	400	394
0.800	0.995	5.443	6.855	3.900	3.995	8.350	0.005	400	398

E. SCENARIO 1 SAM NUMBER SENSITIVITY SSAD-SIM SIMULATION RESULTS

Active SSAD System using S-L-S Firing Policy with Five SAMs

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.500	0.500	4.497	6.455	1.893	2.318	4.560	0.682	400	200
0.600	0.702	5.195	6.702	3.194	2.618	4.200	0.382	400	281
0.700	0.835	5.559	6.811	3.779	2.802	4.035	0.198	400	334
0.800	0.960	6.159	6.920	5.061	2.950	3.595	0.050	400	384

Active SSAD System using S-S-L Firing Policy with Five SAMs

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.500	0.268	4.608	6.587	1.624	2.025	5.000	0.975	400	107
0.600	0.450	5.278	6.859	2.784	2.352	5.000	0.648	400	180
0.700	0.582	5.667	6.893	3.659	2.538	5.000	0.462	400	233
0.800	0.728	6.083	6.935	4.668	2.710	5.000	0.290	400	291

Active SSAD System using S-L-S Firing Policy with Six SAMs

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.500	0.635	4.495	6.402	2.147	2.535	4.978	0.465	400	254
0.600	0.822	5.183	6.648	3.243	2.788	4.462	0.212	400	329
0.700	0.885	5.588	6.861	3.794	2.870	4.160	0.130	400	354
0.800	0.972	6.148	6.934	5.019	2.970	3.645	0.030	400	389

Active SSAD System using S-S-L Firing Policy with Six SAMs

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.500	0.440	5.087	6.713	2.611	2.312	6.000	0.688	400	176
0.600	0.632	5.647	6.836	3.817	2.575	6.000	0.425	400	253
0.700	0.745	5.977	6.905	4.542	2.720	6.000	0.280	400	298
0.800	0.880	6.376	6.944	5.519	2.875	6.000	0.125	400	352

Active SSAD System using S-L-S Firing Policy with Seven SAMs

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.500	0.675	4.522	6.459	2.220	2.625	5.165	0.375	400	270
0.600	0.855	5.247	6.745	3.289	2.832	4.515	0.168	400	342
0.700	0.905	5.594	6.870	3.802	2.898	4.202	0.102	400	362
0.800	0.980	6.139	6.918	5.063	2.980	3.662	0.020	400	392

Active SSAD System using S-S-L Firing Policy with Seven SAMs

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.500	0.668	5.274	6.729	3.233	2.592	6.562	0.408	400	267
0.600	0.840	5.842	6.861	4.375	2.812	6.368	0.188	400	336
0.700	0.918	6.146	6.902	5.037	2.905	6.250	0.095	400	367
0.800	0.975	6.448	6.935	5.753	2.975	6.128	0.025	400	390

Active SSAD System using S-L-S Firing Policy with Eight SAMs

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.500	0.700	4.555	6.478	2.231	2.638	5.178	0.362	400	280
0.600	0.860	5.252	6.760	3.296	2.840	4.525	0.160	400	344
0.700	0.905	5.599	6.874	3.806	2.898	4.200	0.102	400	362
0.800	0.972	6.061	6.919	4.821	2.972	3.745	0.028	400	389

Active SSAD System using S-S-L Firing Policy with Eight SAMs

SAM P_{kill}	$P_{noleakers}$	Average Threat Kill Range	Maximum Threat Kill Range	Minimum Threat Kill Range	Average Number of Killed Threats	Average Number of Expended SAMs	Average Number of Leakers	Total Run Number	Total Successful Ship Defense
0.500	0.755	5.333	6.734	3.386	2.735	7.110	0.265	400	302
0.600	0.890	5.837	6.856	4.449	2.872	6.735	0.128	400	356
0.700	0.960	6.151	6.898	5.128	2.960	6.490	0.040	400	384
0.800	0.990	6.460	6.938	5.764	2.990	6.255	0.010	400	396

APPENDIX E: COMPARATIVE ANALYSIS TABLES

A. COMPARATIVE ANALYSIS FOR SCENARIO 1

1. Comparative Analysis for the Primary MOE (Probability of No Leakers)

Semi-active SSAD System					
SAM P_{kill}	**Firing Policy**	**$P_{noleakers}$**	**Test Statistics**	**P-value**	**Result**
0.60	S-L-S	0.550	12.008	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.828			
0.65	S-L-S	0.680	7.599	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.842			
0.70	S-L-S	0.700	8.721	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.878			
0.75	S-L-S	0.782	5.837	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.890			
0.80	S-L-S	0.865	6.540	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.958			
Active SSAD System					
SAM P_{kill}	**Firing Policy**	**$P_{noleakers}$**	**Test Statistics**	**P-value**	**Result**
0.60	S-L-S	0.845	4.890	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.950			
0.65	S-L-S	0.898	3.940	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.968			
0.70	S-L-S	0.900	4.010	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.970			
0.75	S-L-S	0.950	3.310	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.990			
0.80	S-L-S	0.980	2.410	0.007	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.998			

Table E.1. $P_{noleakers}$ values with respect to firing policies for Scenario 1.

SAM P_{kill}	SSAD System	$P_{noleakers}$	Test Statistics	P-value	Result
0.60	Active	0.950	4.722	0.000	Active SSAD system provides higher $P_{noleakers}$.
	Semi-active	0.828			
0.65	Active	0.968	6.077	0.000	Active SSAD system provides higher $P_{noleakers}$.
	Semi-active	0.842			
0.70	Active	0.970	4.902	0.000	Active SSAD system provides higher $P_{noleakers}$.
	Semi-active	0.878			
0.75	Active	0.990	5.950	0.000	Active SSAD system provides higher $P_{noleakers}$.
	Semi-active	0.890			
0.80	Active	0.998	5.360	0.000	Active SSAD system provides higher $P_{noleakers}$.
	Semi-active	0.958			

Table E.2. Scenario 1 Active vs. Semi-active SSAD System Comparison Analysis Table of Probability of no leakers. Both SSAD systems use S-S-L Firing Policy.

2. Comparative Analysis for the Intermediate MOEs

a) Comparative Analysis for average number of expended SAMs

Semi-active SSAD System					
SAM P_{kill}	**Firing Policy**	**Av.Number of exp. SAMs**	**Test Stats.**	**P-value**	**Result**
0.60	S-L-S	3.908	45.200	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	6.532			
0.65	S-L-S	3.818	46.200	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	6.442			
0.70	S-L-S	3.775	48.050	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	6.312			
0.75	S-L-S	3.682	57.680	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	6.188			
0.80	S-L-S	3.528	64.180	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	6.155			
Active SSAD System					
SAM P_{kill}	**Firing Policy**	**Av.Number of exp. SAMs**	**Test Stats.**	**P-value**	**Result**
0.60	S-L-S	4.642	25.290	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	6.868			
0.65	S-L-S	4.275	30.250	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	6.65			
0.70	S-L-S	4.162	31.946	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	6.575			
0.75	S-L-S	3.905	37.300	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	6.360			
0.80	S-L-S	3.730	43.960	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	6.225			

Table E.3. Average number of expended SAM values with respect to firing policies for Scenario 1.

SAM P_{kill}	SSAD System	Av.Number of exp.SAMs	Test Stats	P-value	Result
0.60	Active	6.532	4.250	0.000	Active SSAD System expends more SAMs.
	Semi-active	6.868			
0.65	Active	6.442	2.870	0.002	Active SSAD System expends more SAMs.
	Semi-active	6.650			
0.70	Active	6.312	3.930	0.000	Active SSAD System expends more SAMs.
	Semi-active	6.575			
0.75	Active	6.188	3.440	0.000	Active SSAD System expends more SAMs.
	Semi-active	6.360			
0.80	Active	6.155	1.670	0.0470	Active SSAD System expends more SAMs.
	Semi-active	6.225			

Table E.4. Scenario 1 Active vs. Semi-active SSAD System Comparison Analysis Table of Average Number of Expended SAMs. Both SSAD systems use S-S-L Firing Policy.

b) Comparative Analysis for average kill range of threats

Semi-active SSAD System					
SAM P_{kill}	**Firing Policy**	**Av.threat kill range (NM)**	**Test Stats.**	**P-value**	**Result**
0.60	S-L-S	3.508	9.860	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	4.378			
0.65	S-L-S	3.831	8.240	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	4.493			
0.70	S-L-S	3.952	9.350	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	4.662			
0.75	S-L-S	4.166	10.050	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	4.849			
0.80	S-L-S	4.45	8.100	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	4.953			
Active SSAD System					
SAM P_{kill}	**Firing Policy**	**Av.threat kill range (NM)**	**Test Stats.**	**P-value**	**Result**
0.60	S-L-S	5.130	9.250	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	5.875			
0.65	S-L-S	5.510	7.700	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	6.068			
0.70	S-L-S	5.625	7.820	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	6.168			
0.75	S-L-S	5.893	7.470	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	6.354			
0.80	S-L-S	6.076	7.330	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	6.471			

Table E.5. Average kill range of threats values with respect to firing policies for Scenario 1.

SAM P_K	SSAD System	Av.threat kill range (NM)	Test Stats.	P-value	Result
0.60	Active	5.875	21.160	0.000	Active SSAD System has longer kill range.
	Semi-active	4.378			
0.65	Active	6.068	24.090	0.000	Active SSAD System has longer kill range.
	Semi-active	4.493			
0.70	Active	6.168	26.460	0.000	Active SSAD System has longer kill range.
	Semi-active	4.662			
0.75	Active	6.354	33.460	0.000	Active SSAD System has longer kill range.
	Semi-active	4.849			
0.80	Active	6.471	40.460	0.000	Active SSAD System has longer kill range.
	Semi-active	4.849			

Table E.6. Scenario 1 Active vs. Semi-active SSAD System Comparison Analysis Table of Average Kill Range of Threats. Both SSAD systems use S-S-L Firing Policy.

B. COMPARATIVE ANALYSIS FOR SCENARIO 2

1. Comparative Analysis for the Main MOE (Probability of No Leakers)

Semi-active SSAD System					
SAM P_{kill}	**Firing Policy**	**$P_{noleakers}$**	**Test Statistics**	**P-value**	**Result**
0.60	S-L-S	0.142	08.930	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.500			
0.65	S-L-S	0.180	11.260	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.565			
0.70	S-L-S	0.192	14.130	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.688			
0.75	S-L-S	0.338	10.590	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.712			
0.80	S-L-S	0.422	12.740	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.855			
Active SSAD System					
SAM P_{kill}	**Firing Policy**	**$P_{noleakers}$**	**Test Statistics**	**P-value**	**Result**
0.60	S-L-S	0.775	6.780	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.942			
0.65	S-L-S	0.812	7.050	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.968			
0.70	S-L-S	0.902	4.080	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.972			
0.75	S-L-S	0.925	5.050	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.995			
0.80	S-L-S	0.960	3.720	0.000	S-S-L firing Policy provides higher $P_{noleakers}$.
	S-S-L	0.998			

Table E.7. Semi-active SSAD system $P_{noleakers}$ values with respect to firing policies for Scenario 2.

SAM P_{kill}	SSAD System	$P_{noleakers}$	Test Statistics	P-value	Result
0.60	Active	0.942	13.940	0.000	Active SSAD system provides higher $P_{noleakers}$.
	Semi-active	0.500			
0.65	Active	0.968	13.460	0.000	Active SSAD system provides higher $P_{noleakers}$.
	Semi-active	0.565			
0.70	Active	0.972	10.690	0.000	Active SSAD system provides higher $P_{noleakers}$.
	Semi-active	0.688			
0.75	Active	0.995	11.320	0.000	Active SSAD system provides higher $P_{noleakers}$.
	Semi-active	0.712			
0.80	Active	0.998	07.730	0.000	Active SSAD system provides higher $P_{noleakers}$.
	Semi-active	0.855			

Table E.8. Scenario 2 Active vs. Semi-active SSAD System Comparison Analysis Table of Probability of no leakers. Both SSAD systems use S-S-L Firing Policy.

2. Comparative Analysis for the Intermediate MOEs

a) Comparative Analysis for average number of expended SAMs

Semi-active SSAD System					
SAM P_{kill}	**Firing Policy**	**Av.Number of exp. SAMs**	**Test Stats.**	**P-value**	**Result**
0.60	S-L-S	4.012	728.100	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	8.000			
0.65	S-L-S	4.022	549.000	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	8.000			
0.70	S-L-S	4.022	549.000	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	8.000			
0.75	S-L-S	4.012	728.100	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	8.000			
0.80	S-L-S	4.008	954.270	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	8.000			
Active SSAD System					
SAM P_K	**Firing Policy**	**Av.Number of exp. SAMs**	**Test Stats.**	**P-value**	**Result**
0.60	S-L-S	6.155	39.100	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	9.195			
0.65	S-L-S	6.058	32.500	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	8.840			
0.70	S-L-S	5.570	38.030	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	8.695			
0.75	S-L-S	5.120	45.760	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	8.485			
0.80	S-L-S	4.982	49.760	0.000	S-S-L firing Policy expends more SAMs.
	S-S-L	8.380			

Table E.9. Average number of expended SAM values with respect to firing policies for Scenario 2.

SAM P_{kill}	SSAD System	Av.Number of exp.SAMs	Test Stats	P-value	Result
0.60	Active	9.195	21.700	0.000	Active SSAD System expends more SAMs.
	Semi-active	8.000			
0.65	Active	8.840	13.850	0.000	Active SSAD System expends more SAMs.
	Semi-active	8.000			
0.70	Active	8.695	12.150	0.000	Active SSAD System expends more SAMs.
	Semi-active	8.000			
0.75	Active	8.485	10.240	0.000	Active SSAD System expends more SAMs.
	Semi-active	8.000			
0.80	Active	8.380	08.260	0.000	Active SSAD System expends more SAMs.
	Semi-active	8.000			

Table E.10. Scenario 2 Active vs. Semi-active SSAD System Comparison Analysis Table of Average Number of Expended SAMs for Scenario 2. Both SSAD systems use S-S-L Firing Policy.

b) Comparative Analysis for average kill range of threats

Semi-active SSAD System					
SAM P_{kill}	**Firing Policy**	**Av.threat kill range (NM)**	**Test Stats.**	**P-value**	**Result**
0.60	S-L-S	3.028	07.220	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	3.529			
0.65	S-L-S	3.105	08.010	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	3.650			
0.70	S-L-S	3.189	10.260	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	3.832			
0.75	S-L-S	3.463	07.130	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	3.899			
0.80	S-L-S	3.653	08.740	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	4.129			
Active SSAD System					
SAM P_{kill}	**Firing Policy**	**Av.threat kill range (NM)**	**Test Stats.**	**P-value**	**Result**
0.60	S-L-S	5.174	10.120	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	5.871			
0.65	S-L-S	5.241	13.430	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	6.092			
0.70	S-L-S	5.625	09.510	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	6.206			
0.75	S-L-S	5.964	07.900	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	6.366			
0.80	S-L-S	6.066	06.280	0.000	S-S-L firing Policy has longer kill range.
	S-S-L	6.425			

Table E.11. Average kill range of threats values with respect to firing policies for Scenario 2.

SAM P_K	SSAD System	Av.threat kill range (NM)	Test Stats.	P-value	Result
0.60	Active	5.875	21.160	0.000	Active SSAD System has longer kill range.
	Semi-active	4.378			
0.65	Active	6.068	24.090	0.000	Active SSAD System has longer kill range.
	Semi-active	4.493			
0.70	Active	6.168	26.460	0.000	Active SSAD System has longer kill range.
	Semi-active	4.662			
0.75	Active	6.354	33.460	0.000	Active SSAD System has longer kill range.
	Semi-active	4.849			
0.80	Active	6.471	40.460	0.000	Active SSAD System has longer kill range.
	Semi-active	4.849			

Table E.12. Scenario 2 Active vs. Semi-active SSAD System Comparison Analysis Table of Average Kill Range of Threats. Both SSAD systems use S-S-L Firing Policy.

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